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HIGH ALTITUDE RETARDANT DROP MECHANIZATION STUDY

Final Report
Volume II

CAPTURE OF RETARDANTS IN VERTICAL FUELS

Northern Forest Fire Laboratory
Missoula, Montana

A report of research performed under the auspices of the Intermountain Forest and Range Experiment Station, Northern Forest Fire Laboratory, Missoula, Montana.

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CAPTURE OF RETARDANTS IN VERTICAL FUELS

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Northern Forest Fire Laboratory
Missoula, Montana

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FOREWORD

This document presents results of a study to assess the ability of aerially delivered retardants to treat the vertical fine fuels. Hitherto, this subject has not been treated analytically, nor has there been adequate experimental work to fully validate the results and conclusions. This document represents a first attempt to organize and deal with the information available on the subject, and as a result opens up potential areas for more detailed study. Even in this form, with the acceptance of the uncertainties inherent in initial work of this nature, the basic study allows us to make reasonable conclusions regarding important factors in achieving fuels coverage. The findings are not revolutionary in terms of important parameters. Indeed, they show remarkable agreement with coverage levels previously established on the basis of observation and experience. The findings are, however, suprising in regard to details of operation, and they suggest potentially rewarding investigations for future consideration.

The work is in essence a computer-managed marriage between Forest Hydrology, forest fuels, and retardant physics studies. This volume is offered not as a final word, but as a potential beginning of the characterization and understanding of an important factor in Fire Management and Control.

TABLE OF CONTENTS

Section		Page
I	INTRODUCTION AND SUMMARY	1
	How A Vegetation Stand Wets Out	1
	The Grah-Wilson Film Thickness Parameter	3
	The Mean Tree	3
	Relation of Retardants to the Grah-Wilson Water Film Parameter	4
II	DISCUSSION OF RESULTS	5
	Retardant Input to Achieve Saturation	5
	Retardant Effects on Spread Rate	8
	Crown Effects	8
	Chaparral	9
	Grass and Litter	13
	Application of the Capture Model to Fire Spread	15
III	DISCUSSION OF THE MODEL	16
	Hamilton-Rowe Experiments	21
	Grah-Wilson Experiment	24
	The Computational Model	26
	Conclusion	40
APPENDIX A	Douglas Fir Data	41
APPENDIX B	Chaparral Bush Data	49
APPENDIX C	Relationship of Film Thickness to Rheological Properties	56
APPENDIX D	Capture Programs	63

LIST OF FIGURES

Figure		Page
1	Grah-Wilson Film Thickness Value Applied to Douglas Fir	6
2	Grah-Wilson Film Thickness Value Applied to Chaparral	7
3	Effect of Retardant Input on Weighted Retardant Damping Coefficient, Fir Tree	9
4	Effect of Salt Content on Fir Tree at Two Thickness Levels	10
5	Effect of Retardant Input on Weighted Mineral Damping Coefficient, Chaparral	11
6	Effect of Salt Content on Chaparral at Two Thickness Levels	12
7	Application Rate Required for Saturation of Grass and Litter	14
8	Rainfall Interception, Spring and Summer Storms	23
9	Grah-Wilson Experimental Data	25
10	Geometrical Representation of Chaparral Bush	31

LIST OF TABLES

Table		Page
I	Some Interception Storage Values Reported for Vegetation in the American Literature[8]	19
II	Characteristics of Raindrops and Precipitation of Different Forms[9]	21
III	Hamilton-Rowe Experimental Data[7]	23
IV	Stand Data, Single Crown Tree	28
V	Stand Data, Mixed Brush	29

I. INTRODUCTION AND SUMMARY

One of the objectives of the High-Altitude Delivery System contract was analysis leading to the understanding of improved methods of aerial retardant dispensing. The tradeoff between desirable retardant characteristics for delivery from the aircraft to the ground and those for effective uniform coating of the fine fuels is a primary issue. Recognition of this tradeoff led to negotiation of a contractual agreement to model vertical retardant distribution in the fine fuels using some of the forest simulation techniques developed by Honeywell for evaluating bomb fuze performance in trajectories passing through trees.

Although card decks on tree transects including much of the fine fuels were obtained from the Army Waterways Experiment Station, Vicksburg, Mississippi, the initially contemplated approach was not implemented because the effects of retardants, unlike fuzes, are dominated by the fine fuels rather than the branchwoods. Instead, a more abstract representation of vegetation elements was selected to place the emphasis on the fine fuels.

The basic approach selected was to organize physical data on two typical vertical fuel targets --Douglas Fir tree crowns and chaparral brush. Fuel distribution descriptions were furnished by the USDA Forest Service. Included in the basic approach was a method of relating this physical data to the wetting-out process as a function of retardant characteristics and gallons per 100 square feet (gpc) planar treatment levels.

HOW A VEGETATION STAND WETS OUT

The first problem encountered was a general description of the wetting-out process. Unfortunately, it cannot be represented by a singular phenomenon, and the dominant features change with different methods of application. The

observation that aerially delivered retardants have the characteristics of a very heavy rainfall of extremely short duration leads to the contention that the phenomenon is most directly related to a relatively large volume of forest hydrology studies.

Analogizing retardant delivery to rainfall is a convenient way of avoiding the complex physical process description involved in capture phenomena. Some of these processes are:

Application: Retardant particle size and velocity distributions, time duration of the application

Interception: Probability of capture by fine fuel elements, droplet shattering, coalescing, dripping, and running

Interfacial: Surface conditions of retardant droplet and fuel elements.

In dealing with this multiplicity of processes, an independent study of each of these is required, along with a method of combining such results with vertical fuel models. Such an approach would be a formidable undertaking.

As an example of this multiplicity, one of the authors examined the wetting-out process of vegetation during a thunderstorm. Some of the observations were the following.

In rain, Colorado Spruce needles do not wet out per se, but capture ballistically shattered droplets that through a process of combining, splattering, and dripping produce relatively uniform coverage throughout the trees. The barked wood in the stems, however, wets out to film thickness and sustains flow. Other species, such as arborvitae and most broad leafs, wet out after dust is washed off in the initial shower.

THE GRAH-WILSON FILM THICKNESS PARAMETER

This large diversity of factors is reconciled by a factor called the Grah-Wilson film thickness.[1] It is determined (in the case of water) by noting the change in weight of a tree as water is applied. When the change in weight damps to zero, the amount of water on the tree is converted to an equivalent thickness assumed to be uniformly applied over the tree surface area. This equivalent film thickness changes from species to species reflecting different surface affinities and fine fuel density values. It is also reduced if the tree is shaken, which might represent high wind or driving rain.

The variation of the equivalent film thickness due to vegetation differences and winds is not believed critical to the conclusion of this study. Typical values representing a film thickness for the stand can be selected to represent the expected retention. In the Grah-Wilson experiments, Monterey Pine had a film thickness of 0.003 inch and Kidneywort Baccharis had a film thickness of 0.007 inch after drip. These values were reduced by a factor of two after shaking. This film thickness is the limit of retention by the fine fuels. The surface areas of the vegetation element are treated in the capture program, and by this assumption the retained retardant salts can be estimated for given vertical organizations of the fine fuels.

THE MEAN TREE

To represent a range of fuels, two techniques were used. The characteristics of a typical Douglas Fir, supplied by the Forest Service, were used in a sectored geometrical representation. The characteristics of a typical chaparral field, again supplied by the Forest Service, were applied to a geometrical representation of a single chaparral bush, although no such species actually exists in the mixed brush field. Both assumptions are normative in that these representations give us a standard for comparing various retardant effects without regard for extreme cases.

RELATION OF RETARDANTS TO THE GRAH-WILSON WATER FILM PARAMETER

Retardants can be related to the water film thickness by experimenting with surface film thickness in dip tests on a flat or complex surface. More precise values can also be obtained through a number of potential test techniques. Although such tests should be considered, particularly in determining precise rheological relationships to the Grah-Wilson parameter, they are more elaborate and are beyond the scope of the present delivery study. Current retardants appear to reside between 4:1 and 15:1 on the retardant-to-water film basis.

To estimate the increase in retention afforded by typical retardants, a series of dip tests was conducted both by Honeywell and the U.S. Forest Service. The results, though far from definitive, suggested that retardant film thickness could be approximated by about four times the equivalent water film thickness. Consequently, the film thickness value for Douglas Fir was established at 0.012 inch and for the chaparral field at 0.028 inch.

II. DISCUSSION OF RESULTS

RETARDANT INPUT TO ACHIEVE SATURATION

Figures 1 and 2 show the Grah-Wilson film thickness value as a function of gpc planar input above the trees for Douglas Fir and chaparral. Different levels of saturation allow consideration of the possibility that some fuel surfaces are more important than others. Retardant effectiveness is maximized when the fuel coating is uniform, a condition that can only be asserted at saturation level A. When levels B or C are saturated, some degree of coverage has normally been achieved in the unsaturated areas.

Bench marks on the figure show dip tests conducted by the Forest Service and Honeywell and indicate the extremes of variability that might be expected if the saturated vegetation were vigorously shaken. For high-altitude delivery, the appropriate film values expected are near the static film thickness levels. High-drop impact energies from low-level delivery may drive the thickness values downward, as will a high variable wind after delivery.

The effect of changing angle of attack from vertical, as in lower altitude delivery, changes the way in which the vegetation saturates. Exploration of this phenomenon requires a modification to the basic model which, though potentially of value in more general studies, is unnecessary where higher altitude delivery is the primary issue. Angular penetration followed by vertical dripping is a considerably different case dominated perhaps by the velocity of the retardant, with a liklihood in dense vegetation of not achieving saturation of the leeward segments of the tree.

Figure 2 shows that in high-density fuels saturation is very difficult to achieve, particularly if the predicted equivalent Grah-Wilson film thicknesses are accurate. A similar situation might occur if a very dense crown stand had been selected.

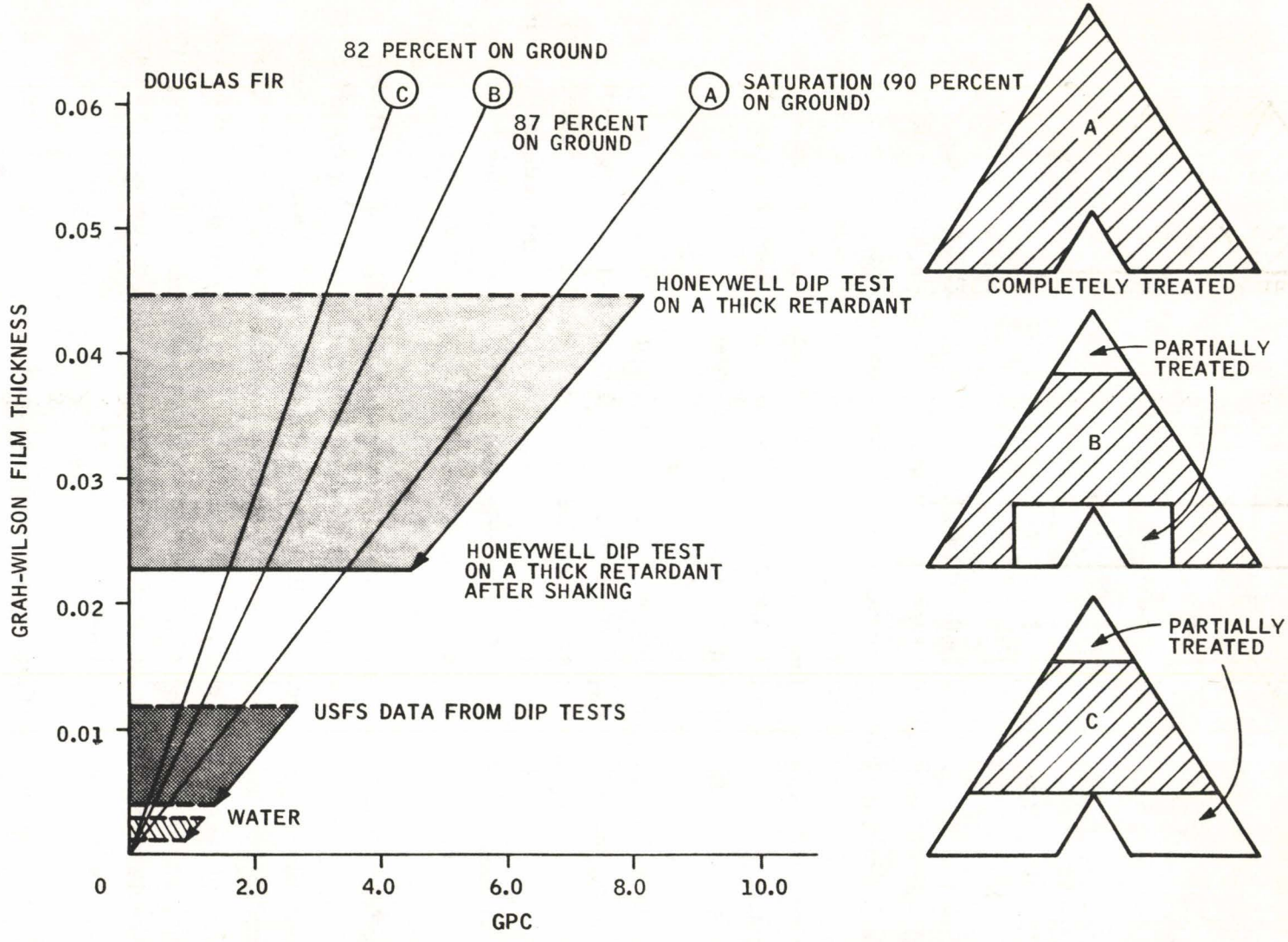


Figure 1. Grah-Wilson Film Thickness Value Applied to Douglas Fir

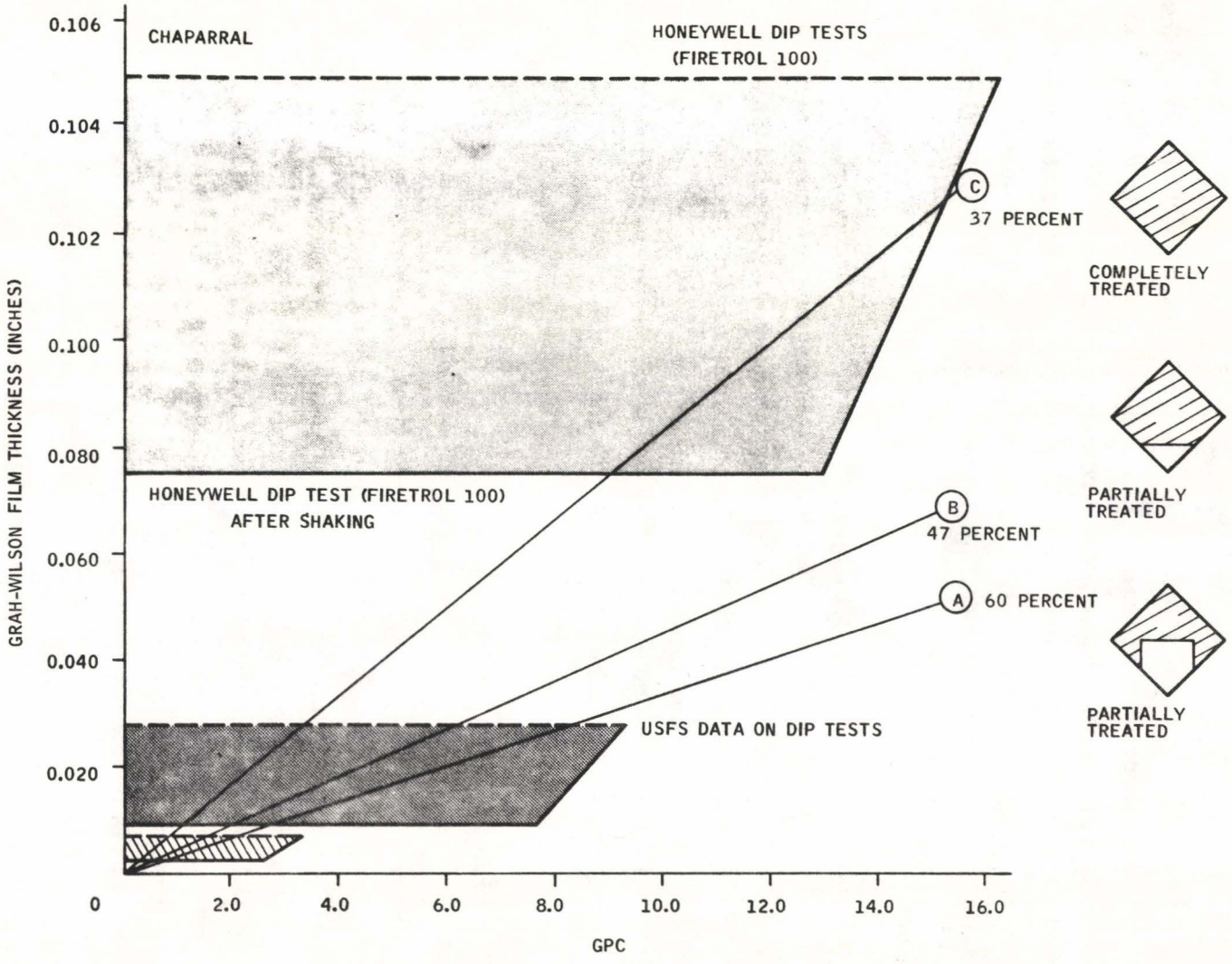


Figure 2. Grah-Wilson Film Thickness Value Applied to Chaparral

RETARDANT EFFECTS ON SPREAD RATE

To assess the effect of various retardant film thicknesses, salt concetrations, and the relative importance of achieving total saturation, the model was also modified to include the calculation of the retardant damping coefficient (η_r)[2] using curves furnished by the Forest Service for typical fuels that contained a specified initial mineral content. (The water damping coefficient was not considered, although in the thick films delivered near the fire its effects might be significant.)

A full matrix of runs appears in Appendices A and B of this report, and includes calculation of η_r for the fuel complex using three weighting techniques. For purposes of this discussion a weighted η_r based on ascribing relative importance to certain areas of the vegetation will be used. Because we are interested primarily in the values at saturation (when coverage becomes uniform), the differences between results are of no great consequence to qualitative interpretation presented in this discussion.

CROWN EFFECTS

Figure 3 shows the effect of various applied planar concentrations on the retardant damping coefficient for the range of film thicknesses believed to be typical. The degree of saturation of the fir tree crown is shown in the intersecting curves labelled levels A, B, and C, corresponding to that suggested in Figure 1. These graphs show what has been intuitively believed -- that thicker retardants are better than thin in the treatment of crown fuels. The region bounded by the four points marked (1), (2), (3), and (4) represents the potential area of interest in changing the retardant film thickness.

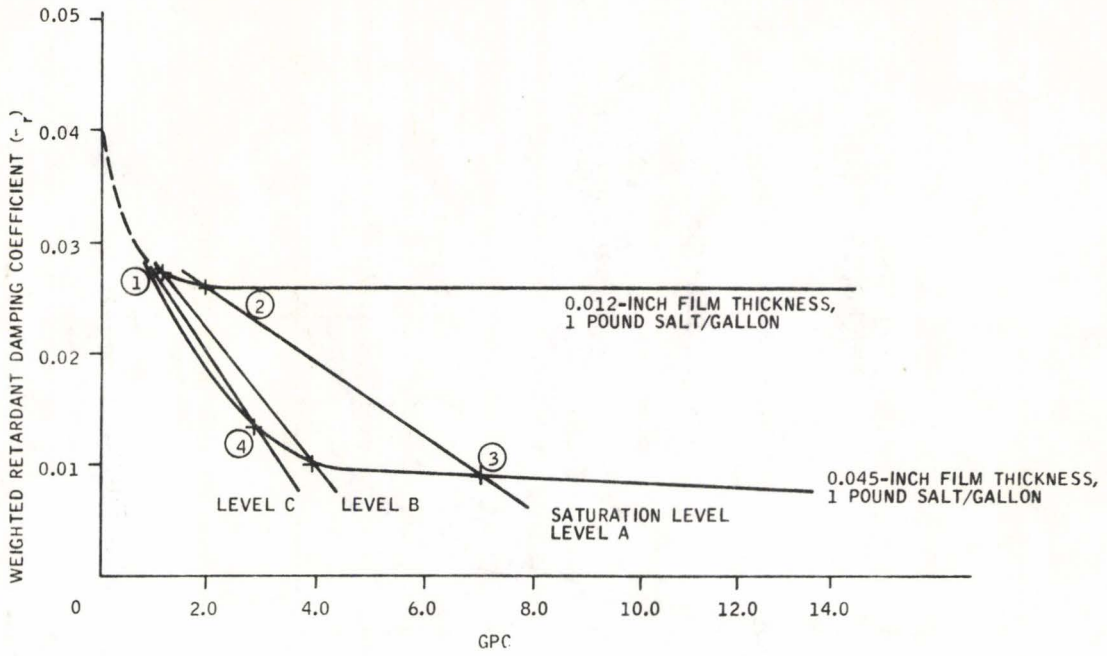


Figure 3. Effect of Retardant Input on Weighted Retardant Damping Coefficient, Fir Tree

Figure 4, however, suggests that the salt content might be increased (over the approximately one pound per gallon currently typical) to some higher value determined by the Grah-Wilson film thickness. The effect shown in the thick film, in which the retardant damping coefficient is zero prior to bush saturation, is an apparent anomaly of the averaging system. It results from the simplifying assumption that in a nonsaturated segment the available salt is uniformly spread, when in fact there are treated and untreated regions within sample levels of the vegetation description. This indicates that there is a salt-to-thickness ratio that is optimum for a given fuel situation.

CHAPARRAL

Unlike tree crown effects, application of the model to chaparral shows a distinct optimum film thickness and an associated optimum salt concentration.

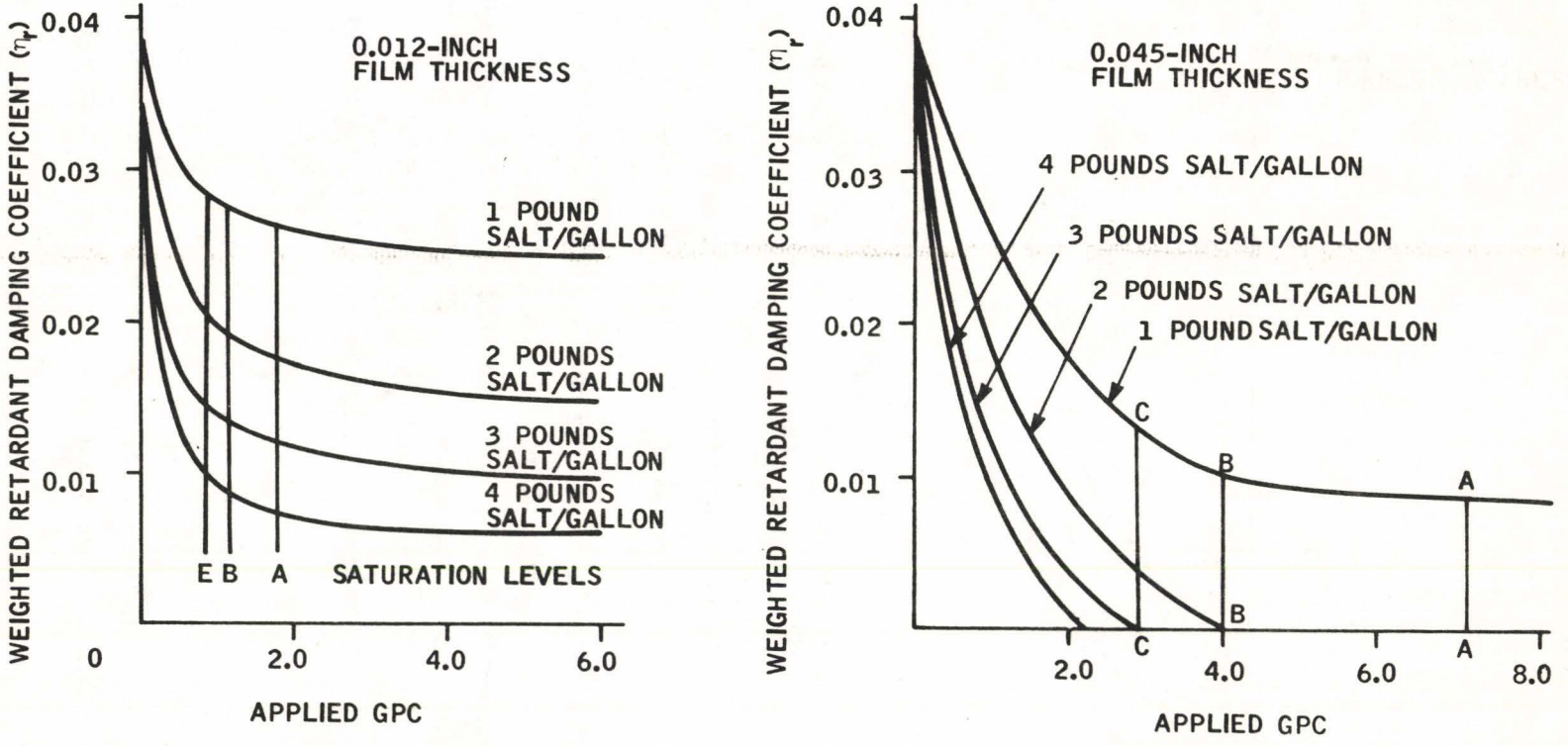


Figure 4. Effect of Salt Content on Fir Tree at Two Thickness Levels

The considerably larger Grah-Wilson film range and the difficulty of achieving saturation yield the curves of Figure 5. Three film thicknesses are shown in the figure: 0.014 inch, 0.028 inch, and 0.105 inch. The 0.028-inch film thickness corresponds to the thickness achieved using the Northern Forest Fire Laboratory dip test data. These curves show a rather unique set of phenomena that are better interpreted by the individual curves in Appendix B.

Some pertinent observations relative to saturation of the bush are shown in Figure 5. For the 0.105-inch film thickness, saturation does not occur at the levels of application shown, whereas saturation occurs for 0.014- and 0.028-inch film thicknesses. The 0.014-inch saturation occurs at 4 gpc.

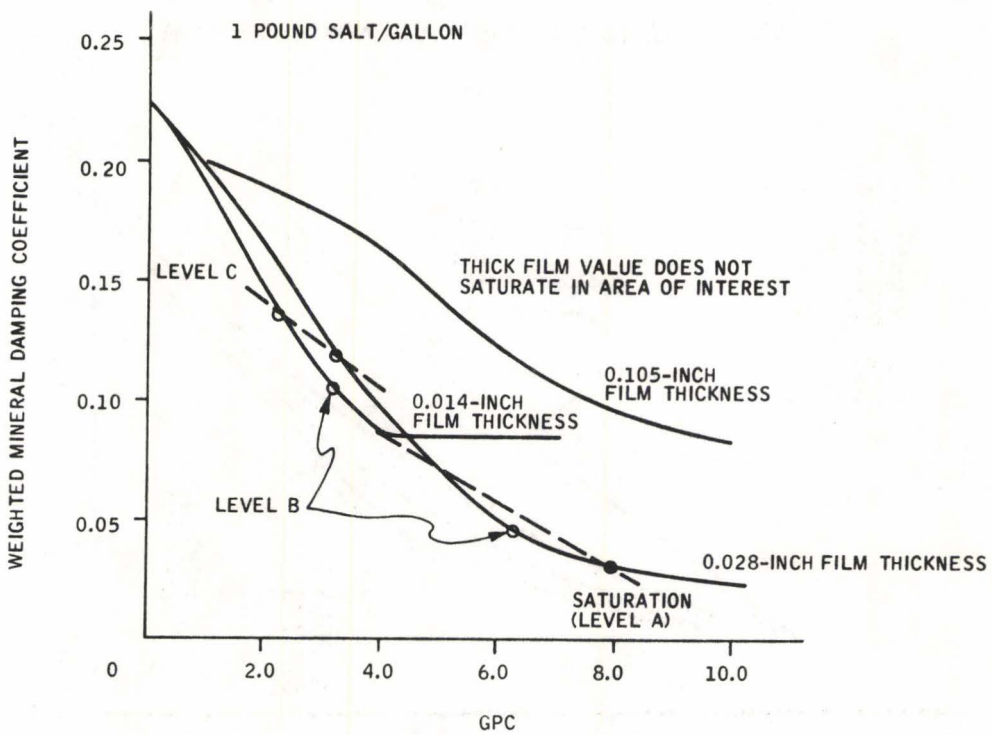


Figure 5. Effect of Retardant Input on Weighted Mineral Damping Coefficient, Chaparral

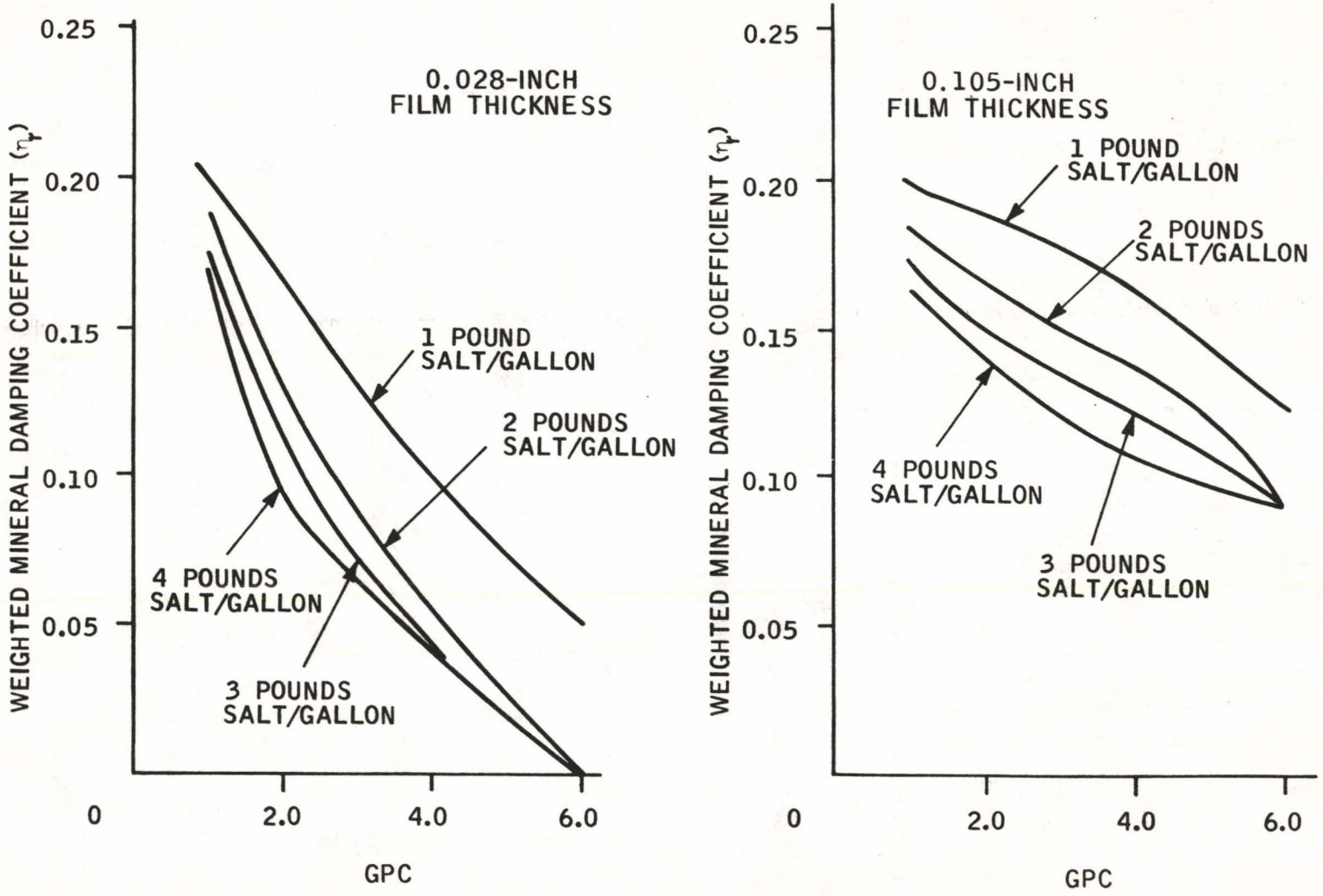


Figure 6. Effect of Salt Content on Chaparral at Two Thickness Levels

and the 0.028-inch film thickness occurs at 8 gpc. At the one-pound-per-gallon level, the weighted mineral damping coefficient cannot be reduced to zero; however, with increased salt content this is possible.

Figure 6 shows the effect of salt content variation. It should be noted, however, that a zero spread rate is projected at 4 gpc with a 0.20-inch film thickness containing three pounds of salt per gallon (see Appendix B). The effects of salt concentration and film thickness show that the thinner retardants are favored in chaparral, whereas in the fir tree the opposite effect was noted.

GRASS AND LITTER

The capture model concept of the average film thickness can also be applied to the grass and litter fine fuels. This calculation involves two steps:

- Determination of the required application rate for coating the fine fuels
- Determination of the required salt for reducing the retardant damping coefficient to zero.

Figure 7 summarizes the application rates for the two fuels:

- The upper curve is for the saturation of litter
- The bottom curve is for grass.

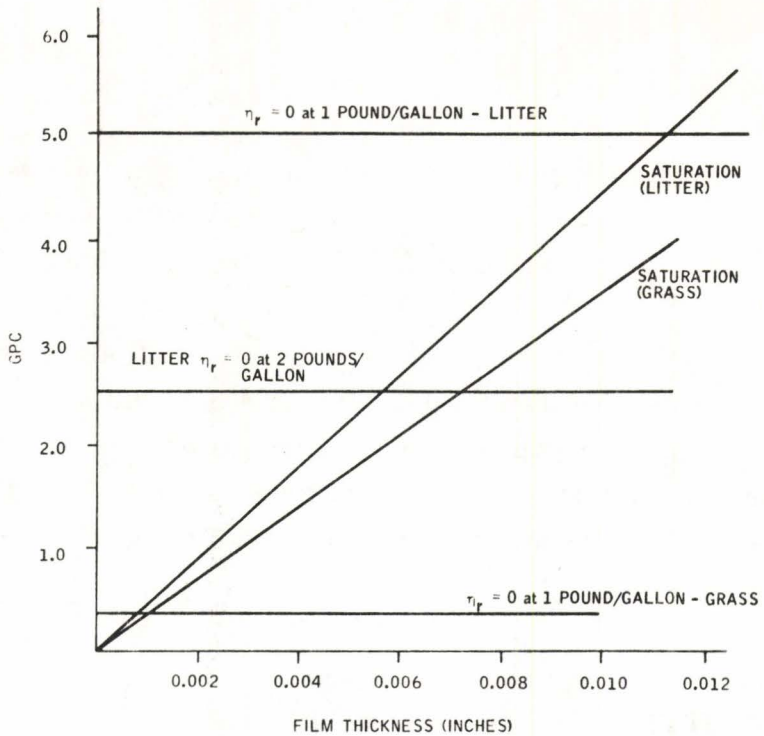


Figure 7. Application Rate Required for Saturation of Grass and Litter

The intercept on the grass curve of 0.4 gpc is limited by the film thickness that can be achieved. Above the minimum film thickness salt intercept, the application rate to zero the retardant damping coefficient is determined by the ability of the retardant to coat the fuels; i.e., a very thin retardant is needed.

Two intercepts for litter are shown that are dependent on the salt content of the retardant. If the thickness is that predicted from Grah-Wilson data on Monterey pine and adjusted for retardants to a 0.012-inch thickness and a salt concentration rate of 1 pound per gallon, then the required delivery rate to reduce retardant damping coefficient to zero is approximately 5.5 gpc. At this rate the tree crowns will be coated, and the litter will also have enough salt to zero η_r. An increase in salt concentration to 2.0 pounds per gallon requires a film thickness of 0.006 inch for $\eta_r = 0$.

APPLICATION OF THE CAPTURE MODEL TO FIRE SPREAD

The next step in the program relates the effect of the captured retardant to the rate of spread through a nomogeneous fuel array with the properties of the stand. This step is based on application of the Rothermel model of fire spread[3], which estimates the rate of spread, R, and the reaction intensity, I_R, using the geometrical properties of the fuels, their arrangement, the quantity of fuels, available heat energy, moisture and mineral properties, and the effect of wind and slope.

To apply this concept to the vertical fuels simulation, we assume that the fire response of each sector of the tree is similar to an equivalent fuel bed treated uniformly to the level predicted by the capture model. The response of the fuel to various treatment levels is then calculated using the retardant damping coefficient, η_r. It is convenient to relate the changes in rate of spread and reaction intensity to Byram's Intensity, which is capable of giving some intuitive feel for real world fires.

Rothermel[4] has shown that Byram's Intensity (BTU-feet/minute) can be expressed in reaction intensity, I_R, and rate of spread, R, if the residence time, t_r, can be approximated.

He has further shown that t_r can be calculated from data generated by Anderson[5], using a weighted surface area to volume ratio, $\tilde{\sigma}$, for the stand. His formula is:

$$I_B = \frac{6.4\ R\ I_R}{\tilde{\sigma}}$$

Using this formula, it can be shown directly that the ratios of Byram's Intensity for treated and untreated fuels vary as the square of the retardant damping coefficient, η_r, varies.

III. DISCUSSION OF THE MODEL

The model of retardant capture is based on the theory of forest interception, which considers the trapping, storage and disposition of materials on the vegetative surfaces. This theory is usually applied to the interception of rain, snow, and fog in studies of the hydrologic cycle of a vegetation stand. The theory of interception can also be applied to other deposited materials, such as retardants, by relating the important variables found in rain interception studies to corresponding properties in retardants.

Leonard[6] defines the total precipitation budget in a vegetated stand by the equation:

$$P = \underbrace{T + D}_{I} + \underbrace{F \pm S - E}_{II}$$

where P = gross precipitation,

T = precipitation passing directly through the canopy,

D = drip from the leaves,

F = stemflow

S = moisture stored on vegetation,

E = evaporation from the vegetative surface.

The first component, I, is the quantity that would be applicable to the litter fuels beneath the canopy, whereas the second component, II, is the quantity that will carry the salts to coat the aerial vegetation.

Following the definitions of Hamilton and Rowe[7], interception is the process in which rainfall is caught by the vegetative canopy and redistributed as throughfall, stemflow, absorption, and evaporation:

- Throughfall is that portion that reaches the ground directly and is dropped from leaves, twigs and stems.
- Stemflow is that portion that reaches the ground by running down the stems.
- Interception loss is that portion retained by the aerial part of the vegetation and is either absorbed or evaporated.
- Storage area is the surface area of leaves, twigs, branches, and stems that can retain water against gravity.
- Storage capacity is the depth of water on the projected area covered by the vegetation that can be stored or detained on the plant surfaces in still air.

These definitions apply to the measurement of interception in vegetation stands, and by suitable change in terminology they are applicable to the delivery of retardants.

On detailed studies of plants, Grah and Wilson[1] further classified the interception of rainfall by vegetation. Surface detention is the water retained by leaves and stems. It has three components:

- Maximum surface detention occurs when the plant surfaces can nold no more water.
- Surface detention after drip occurs in still air after the rain has stopped and the excess has drained from the plant.

- Surface detention after shake is that retained after the excess has drained and the plant has been shaken to simulate maximum air movement.

In terms of storage, these components can be defined as:

- Transitory storage is that component never retained that is lost by drip and evaporation.
- Conditional storage is that component that can be retained by vegetation in still air or lost under the influence of winds.
- Residual storage is that component always retained by the foliage and returned to the air by evaporation.

These definitions suffice to characterize the vertical distribution of retardants in the aerial fuels. An additional definition can be defined for litter interception as that portion intercepted by the litter layer and evaporated without adding to the underlying soil. This definition will not be used in this study because litter is considered as a single layer without a vertical distribution.

Survey of data on interception storage for amounts of rain and snow gives approximate capacities of 0.05 inch of rain for most grasses, shrubs, and trees and 0.15 inch of snow on trees. These data can be used to obtain an approximate range of interception loss for retardants.

The amount of retardant retained will be related to the storage area and the surface tension forces of the retardant on the fine fuels. These surface tension forces will be related to the viscosity of the retardant. Table I shows storage values taken from the literature.

To apply interception theory to retardant capture, it is assumed that delivery is similar to rainfall. The drop size should be of the same order of magnitude,

Table I. Some Interception Storage Values Reported for Vegetation in the American Literature[8]

Vegetation Element	Species	Storage Amount (mm)	Storage Amount (in.)	Reference
Conifers	Abies concolor Lindl.			
	Mature	3.8	0.15*	Kittredge (1953)
	Pole Size	6.6	0.26*	Kittredge (1953)
	Abies magnifica A. Murr.	7.6	0.30*	Kittredge (1953)
	Pinus contorta Dougl.	0.8	0.03	Niederhof and Wilm (1943)
	Pinus lambertiana Dougl.			
	Pinus ponderosa	0.3	0.10*	Kittredge (1953)
	Pinus ponderosa Laws.	3.0	0.12	Rowe and Hendrix (1951)
		0.8-1.3	0.03-0.05	Johnson (1942)
	Second growth	2.3	0.09*	Rowe and Hendrix (1951)
	Mature	2.3	0.09*	Kittredge (1953)
	Young (14 ft. high)	0.3	0.01*	Kittredge (1953)
	Pinus radiata D. Don	0.3-0.1	0.01-0.04[t]	Grah and Wilson (1949)
	Pinus resinosa Ait.	0.8	0.03	Voigt and Zwolinski (1964)
	Picea rubens Sarg. (30 yr. old)	9.1	0.36	Morey in Johnson (1942)
	Pinus strobus L.	0.5	0.02	Voigt and Zwolinski (1964)
	Tsuga canadensis (L.) Carr.	0.8-1.3	0.03-0.05	Horton (1919)
Hardwoods	Aesculus californica (Spach) Nutt.			
	Fall and winter	0.8	0.03	
	Spring and summer	1.3	0.05	Hamilton and Rowe (1949)
	Citrus aurantium L.		0.04	Blaney et. al. (1930)
	Mixed hardwoods (Acer, Ulmus, Quercus, Betula)	0.5-1.8	0.02-0.07	Horton (1919)
	Mixed hardwoods - West Virginia			
	Quercus rubra L., Liriodendron tulipifera L., etc.)			
	Summer	0.5	0.02	
	Winter	0.2	0.006	Trimble and Weitzman (1954)
	Northern hardwoods	2.0	0.08	Morey in Johnson (1942)
	Liquidamber styraciflua L.	0.8	0.03[t]	Paul and Burgy (1961)
	All eastern N. American hardwood data	0.03-1.6	0.001-0.064	Helvey and Patric (1965)

Table I. Some Interception Storage Values Reported for Vegetation in the American Literature[8] (Concluded)

Vegetation Element	Species	Storage Amount (mm)	Storage Amount (in.)	Reference
Shrubs	Adenostoma fasciculatum H & A	1.3-1.5	0.05-0.06[t]	Hicks (1943)
	Baccharis pilularis DC.	0.5-1.5	0.02-0.06[t]	Grah and Wilson (1944)
	Ceanothu cuneatus (Hook) Nutt.,			
	Arctostaphylos mariposa Dudley	1.5	0.06	Hamilton and Rowe (1949)
	Cercocarpus ledifolius Nutt.,	1.0	0.04[t]	Hicks (1943)
	Photinia arbutifolia Lindl.	0.3-1.8	0.01-0.07	Hicks (1943)
	Quercus dumosa Nutt.,			
	Cercocarpus betuliodes Nutt.,			
	Ceanothus crassifolius	2.0	0.08	Hamilton and Rowe (1949)
Grass	Annual grasses-California	1.0-1.5	0.04-0.06[t]	Burgy and Pomeroy (1958)
	Secale cereale L.	1.3	0.05	Horton (1919)
Forest Floor	Liriodendron tulipifera L.,			
	Hicoria spp., Quercus coccinea Muenchh.	1.4	0.057	Helvey (1964)
	Pinus ponderosa Laws			
	20-25 yr.	2.3	0.09	Rowe (1955)
	70-80 yr.	8.1	0.32	Powe (1955)
	140-160 yr.	11.2	0.44	Rowe (1955)
	Pinus radiata D. Don			
	5-10 yr.	0.5	0.02	Rowe (1955)
	10-15 yr.	1.0	0.04	Rowe (1955)
	15-20 yr.	1.8	0.07	Rowe (1955)
	25-30 yr.	3.6	0.14	Rowe (1955)

*Precipitation as rain unless as snow (*) or artificial sprinkling[(t)].

and the entering velocity into the vegetation canopy of the retardant drops should be similar. Table II shows characteristics of rainfall.

Table II. Characteristics of Raindrops and Precipitation of Different Forms[9]

Form	Intensity of Rain (inch/hour)	Median Diameter of Drops (minutes)	Velocity of Fall (fps)
Fog	0.005	0.01	0.01
Mist	0.002	0.1	0.7
Drizzle	0.01	0.96	13.5
Light Rain	0.04	1.24	15.7
Moderate Rain	0.15	1.60	18.7
Heavy Rain	0.60	2.05	22.0
Excessive Rain	1.60	2.40	24.0
Cloudburst	4.00	2.85	25.9
		4.00	29.2
		6.00	30.5

If delivery of retardant is similar to the entry for the cloudburst, the interception theory should apply.

HAMILTON-ROWE EXPERIMENTS

Three rainfall interception studies were conducted in shrub-like vegetation native to California. These studies have shown that the interception loss has a definite relationship to the amount of storm rainfall, and that the amount reaching the ground by stemflow is a significant quantity. The experiments were conducted at the North Fork Experimental Area near Fresno and at San Dimas Experimental Forest in southern California. Data from the North Fork A study area were selected because they are related to laboratory data obtained in Reference 7.

"The North Fork A study area was a 1/20-acre plot in vegetation which had been previously burned and was 19 years old when the study was started in 1937. The vegetation was mostly brush and small trees and included five deciduous species and four evergreen species:

Deciduous species:

California buckeye (Aeseulus californica)
Deerbrush ceanothus (Ceanothus integerrimus)
Pacific poison oak (Rhus diversiloba)
California black oak (Quercus kelloggii)
California frementia (Fremontia californica)

Evergreen species:

Interior live oak (Quercus wislizenii)
Buckbrush ceanothus (Ceanothus cuneatus)
Mountain mahogany (Cercocarpus betuloides)
Mariposa manzanita (Aretostaphylos mariposa)

The crown density of the brush ranged from a minimum of about 20 percent in winter to about 50 percent in late spring and summer. There was a total of 731 stems on the plot, 409 of which were California buckeye. In general the stems were from one-quarter inch to 5 inches in diameter just above the root crown with 70 percent being one inch or less. The shrubs were from 4 to 20 feet high." (7)

The results of the spring and summer storms at North Fork A are shown in Figure 8 and Table III. For mild storms, interception loss varies with intensity until the vegetation is wetted. After this point, the amount of inception changes slowly with the amount of precipitation. A storm of 0.1-inch precipitation corresponds to 6.23 gpc, which is approximately the application level of retardants.

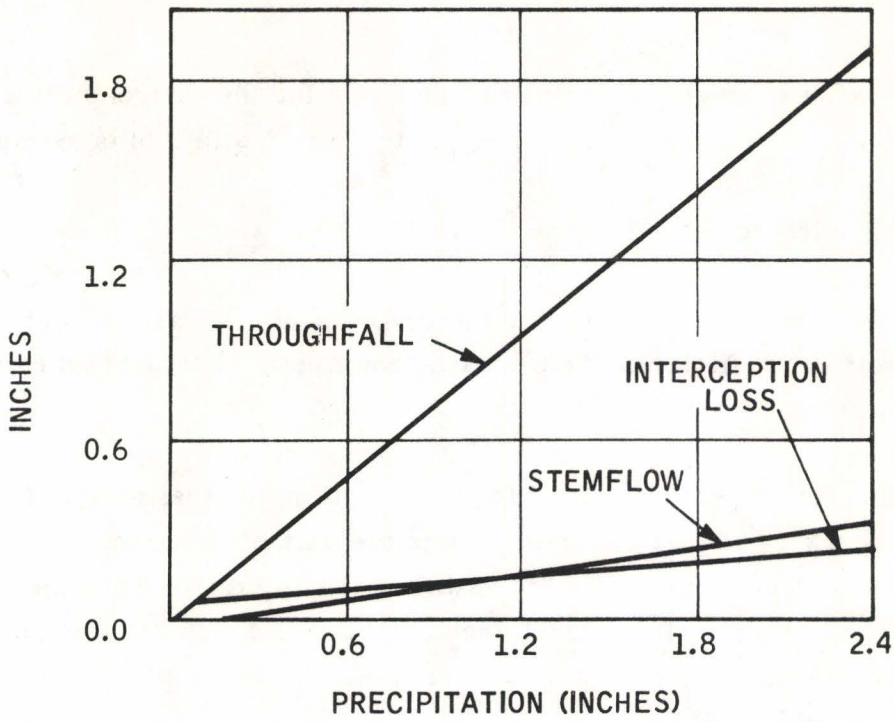


Figure 8. Rainfall Interception, Spring and Summer Storms

Table III. Hamilton-Rowe Experimental Data[7]

	DEPTH (INCH)			
Date	Precipitation	Throughfall	Stemflow	Interception Loss
9/12/39 - 9/13/39	0.10	0.06	Trace	0.04
5/16/38	0.11	0.05	Trace	0.05
9/18/39 - 9/20/39	0.14	0.08	Trace	0.06
5/10/39 - 5/11/39	0.15	0.08	Trace	0.06
10/2/38	0.20	0.14	0.01	0.05
4/23/39	0.21	0.15	0.01	0.05
4/15/40	0.24	0.18	0.02	0.05

Hamilton-Rowe (Page 7) derived an equation for the interception curve for storms of more than 0.3 inch. For North Fork A site this equation is:

$$\text{Interception loss} = 0.070P + 0.050$$

where the first term accounts for the evaporation loss and the second term is the wetting coefficient. This wetting coefficient should be an estimate of the interception storage.

To verify this conjecture, Hamilton-Rowe estimated the total leaf and stem area as 2.6×10^6 square inches. From the data of Reference 1, the film thickness of 0.007 was applied to estimate the volume of water retained by the crowns. This depth is 0.058 inch over the plot, which is in close agreement with the 0.050-inch value in the regression equation.

For mild storms the data in Table III show that the average loss is 0.050 inch, which provides a further test of the interception loss in the range of 0.10 to 0.30 inch of precipitation. This storm intensity is comparable to a retardant drop.

GRAH-WILSON EXPERIMENT

This experiment related the water retained on the surfaces of leaves and stems to surface area by a specially devised experiment. Specimens of Monterey Pine and Kidneywort Baccharis were suspended from a balance in a sheet metal chamber and exposed to sprays that fell only with the force of gravity. The accumulated water was measured at one-minute intervals.

The surface area of the plant was estimated by measurement of green weight, total height, crown height and crown diameter, and, following the interception experiment, oven dry weights were obtained. Representative samples of leaf surfaces were measured and weighed to obtain the surface area of the plants.

Figure 9 is a typical example of the rise and fall of surface detention and its subdivision into storage types.

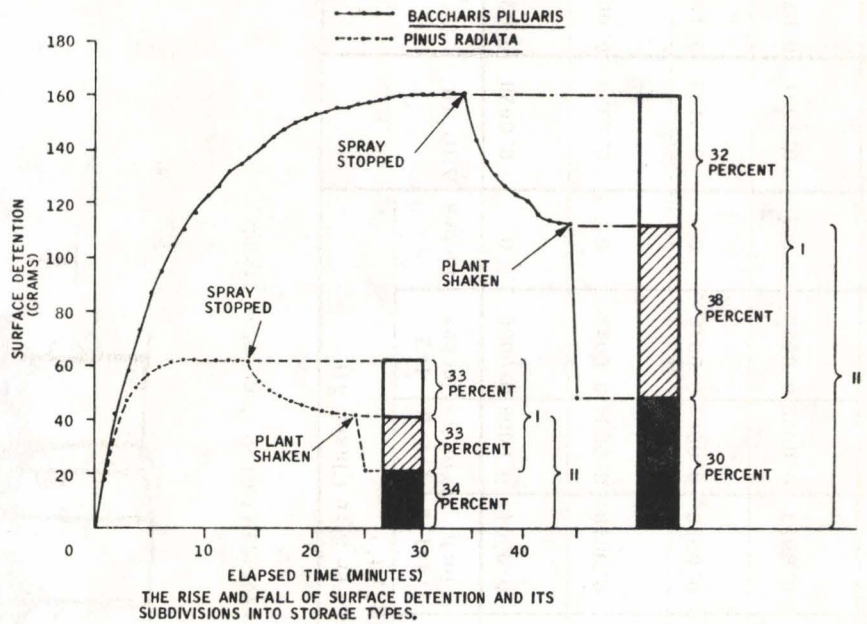


Figure 9. Grah-Wilson Experimental Data

One important conclusion of this study is that leaf surface area cannot be used to explain surface detention without knowledge of the difference due to species. Following the drip, the volume of water retained for both species was related to an equivalent film thickness obtained by dividing the volume retained by the surface area. This thickness is 0.007 inch for the Kidneywort Baccharis and 0.003 inch for the Monterey Pine.

To apply this experiment to retardant application, consideration of the potential film thickness differences between water and retardant is required. Appendix C shows that the thickness will be related to the square root of the viscosity ratio of water and retardant for the long-time drip. This means that thicknesses comparable to snowfall could be achieved.

To apply the interception model to the delivery of fire retardants requires the following information:

- A geometry for the vegetation element (e.g., conical shape for the fir tree)
- A method of estimating the vegetation surface area in the vertical dimension
- A film thickness estimate of the captured retardant
- A variable quantity of retardant applied to the vegetation analogous to rainfall
- A computational scheme to trace the flow through the vegetation element
- A method of evaluating the effectiveness of the coating.

The capture model combines these variables into a single computer model to estimate the performance of a proposed system.

THE COMPUTATIONAL MODEL

The computational model to estimate the vertical distribution of retardant coating consists of the following:

- Fine fuels description in increments of 25 percent of the crown
- Equivalent cylinder conversions
- Flow-through and capture computations
- Salt coating and concentration calculations

- η_r computations
- Averaging of coating and η_r for the complete vegetation element.

Fine Fuels Description

Stand data values considered typical of two vertical fuels were obtained from the USFS and are summarized in Tables IV and V. These data were used to construct segmented models for the capture model, as described in the following subsections.

Equivalent Cylinder Computations

The Douglas Fir tree crown was represented as a cone with a section removed at the base. To represent this geometry for tracing the flow through the crown, it was broken up into small rings and layers, as shown below. Flow of the retardant was traced through each ring into the appropriate layers until it reached the ground.

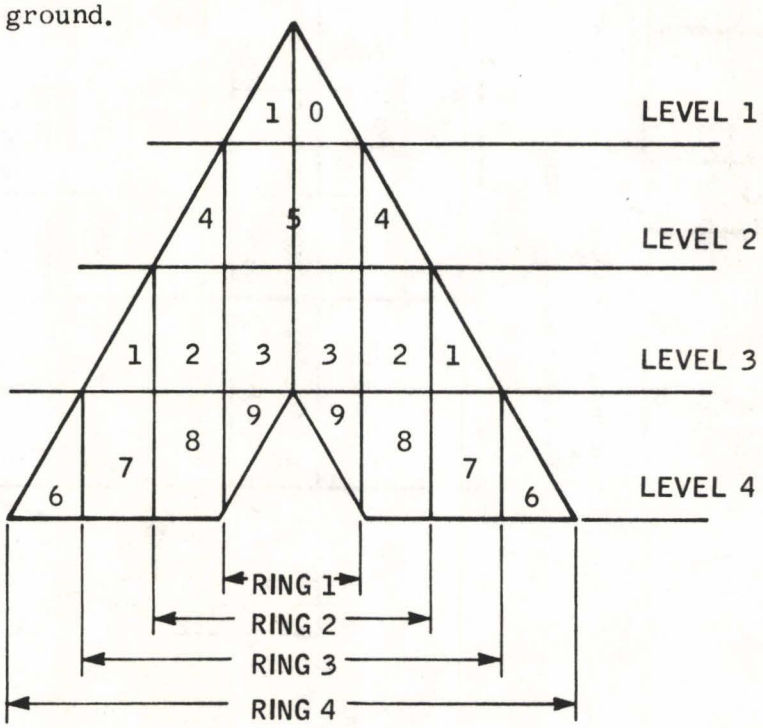
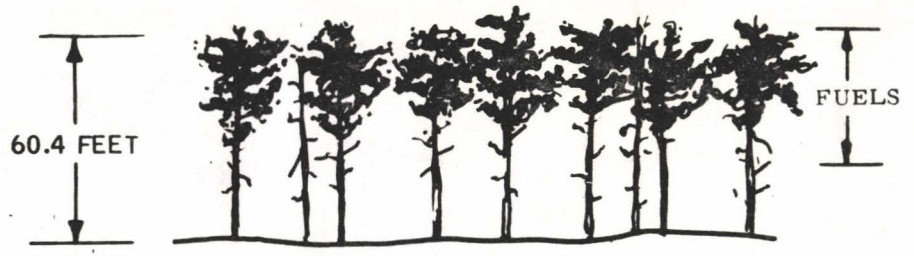
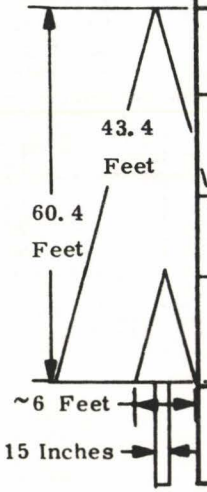


Table IV. Stand Data, Single Crown Tree



Representative Unit: One Tree Crown.

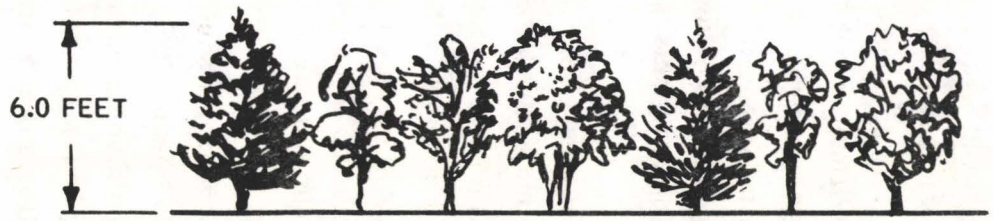
Fuel Distribution: Variable: Crown Coverage 40 to 100 Percent of Stand.



Loading per Category	Surface Area Per Size Class, $\bar{A}ij$ (ft^2/ft^2)							$Ai(ft^2/ft^2)$	$(W_o)i$
	Foliage	0-1/8 Inch	1/8-1/4 Inch	1/4-1/2 Inch	1/2-1 Inch	1-2 Inches	2> Inches		
7.1 Percent x Wo	0.0874	0.0030	0.0006	0.0004	0.0008	0.0006	0	0.0928	0.0237
24.8 Percent x Wo	0.2091	0.0127	0.0027	0.0018	0.0034	0.0022	0	0.2320	0.0828
46.5 Percent x Wo	0.2995	0.0259	0.0056	0.0036	0.0069	0.0049	0	0.3463	0.1552
21.6 Percent x Wo	0.1373	0.0120	0.0026	0.0017	0.0032	0.0023	0	0.1591	0.0721
Percent of Total Weight		9.8	6.4	8.2	31.3	44.3			

Wo = 185 Pounds A_T = 0.83027

Table V. Stand Data, Mixed Brush



Representative Unit: One Square Foot Representing Average Brush Field Characteristics.

Fuel Distribution: Uniform Using the Averaging Assumption.

	Loading per Category	Surface Area Per Size Class, $\bar{A}ij$ (ft^2/ft^2)						$Ai(ft^2/ft^2)$	$(W_o)i$
		Foliage	0-1/4 Inch	1/4-1/2 Inch	1/2-1 Inch	1-2 Inches	2> Inches		
6.0 Feet	21.2 Percent x Wo	0.904	0.146	0.044	0.031	0.026	0.001	1.153	0.1268
	34.2 Percent x Wo	1.459	0.235	0.072	0.051	0.042	0.001	1.859	0.1483
	19.1 Percent x Wo	0.815	0.131	0.040	0.028	0.023	0.001	1.038	0.2781
	25.5 Percent x Wo	1.088	0.175	0.053	0.038	0.031	0.001	1.386	0.1292
	Percent of Total Weight	10.7	17.9	14.6	20.7	34.2	1.9	5.436 ft^2/ft^2 = AT	

Because the amount of vegetation in each of the conical or conical annular regions is smaller than the cylindrical or straight annular sections, these sections were converted into equivalent volume cylinders.

The radius of the cylinder element replacing conical volume element number 10 is given by

$$r_1^1 = \frac{r_1}{\sqrt{3}}$$

where r_1^1 is reduced radius corresponding to equivalent cylinder for the conical section.

This volume element is equivalent to the conical volume, and it provides a convenient method of weighting the amount of vegetation for comparison with the cylindrical element directly beneath.

In the same manner, the volume equivalent radius for element number 4 is given by

$$r_2^1 = \left(\frac{2r_2^2 - r_1^2}{3}\right)^{1/2}$$

where r_2^1 is the reduced radius for section 4.

The radii for elements number one and six are

$$r_3^1 = \left(\frac{3r_3^2 - 2r_2^2}{3}\right)^{1/2}$$

where r_3^1 is the reduced radius for section one, and

$$r_4^1 = \left(\frac{4r_3^2 - 3r_2^2}{3}\right)^{1/2}$$

where r_4^1 is the reduced radius for section six.

The chaparral field, stated to be a representative target, is a mixed species brush field, and the values provided are averages taken across the field. For purposes of the capture model, these values were assumed to apply to a hypothetical bush described geometrically, as shown in Figure 10. It is that hypothetical bush that if grown uniformly in the brush field would produce the values of vertical fuel distribution previously tabulated. This representation is then treated in the same manner as the fir tree to generate the volume in equivalent cylinders.

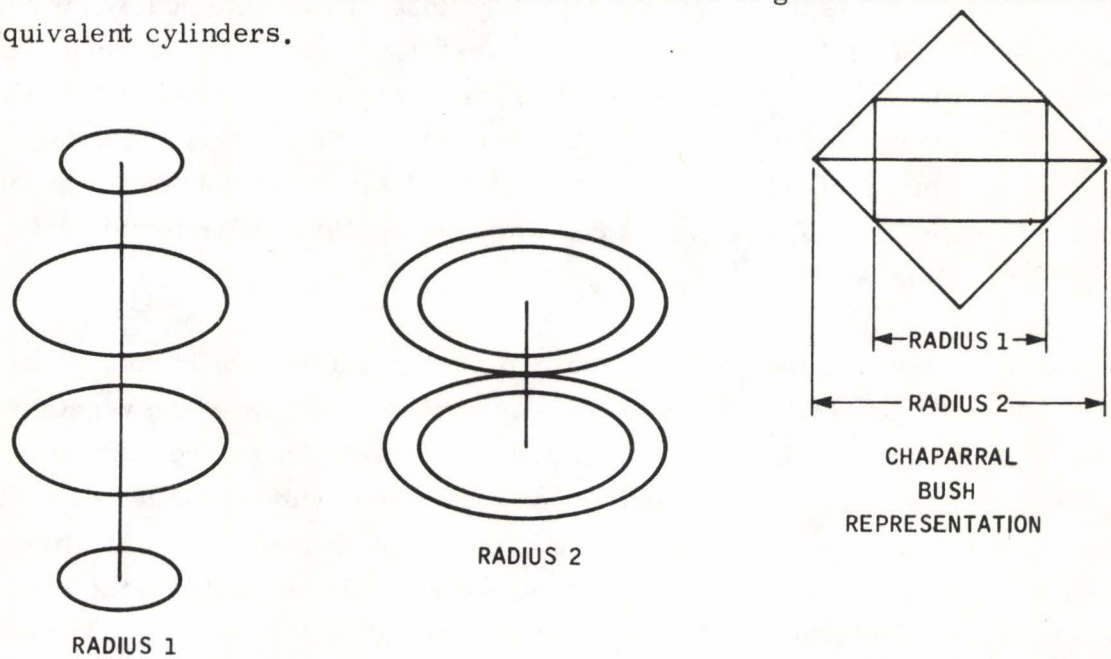


Figure 10. Geometrical Representation of Chaparral Bush

Capture Calculation Model

Capture of retardant is assumed to be proportional to the surface area in a level and the quantity delivered to that level. Capture is limited by a saturation limit based on the Grah-Wilson film thickness. Estimates of these quantities must be made from the fine fuels description, the equivalent cylinder model, and the Grah-Wilson film thickness equivalent.

It is assumed that the quantity of retardant captured in a layer will be directly proportional to the surface area of fine fuels and the incident quantity until maximum film thickness is reached. To illustrate the calculation, consider the upper conical element of the Douglas Fir tree.

The area of the equivalent cylinder is 13.3 square feet so that at an application rate of 1 gpc, 0.133 gallons will be delivered to it. The ratio of the fine fuel area to total area is 0.093 so that 0.0124 gallons will be retained by the fine fuels in an area of 1.07 square feet. Converting gallons to cubic inches and square feet to square inches results in a potential film thickness of 0.0185 inch. The remaining retardant (0.1208 gallon) will drip through to the cylinder below. If retardant delivery is such that calculated film thickness is greater than the potential thickness, the program uses the limit value to calculate the amount of fluid retained.

The film thickness limit is converted into an application rate in gpc. This limit is based on averaging the surface area of all sections of the vegetation description, and on the Grah-Wilson film thickness. Therefore, in the program, the decision logic is based on comparing the incident applied rate with the limit rate to determine the amount captured in each section. An alternative method of calculating these limit quantities could be based on the film thickness and the quantity of surface area from the vegetation description.

The program follows sequentially the vertical flow through the vegetation using the logic discussed earlier. This produces detailed data for each level and ring on the amount captured, the amount that drips through to the next level, the gallons captured per square foot, and the percent coated. These data are the output for the cells. Finally, the quantity reaching the ground is tabulated, and the gpc for each ring is printed.

As a final summary, the total amount on the ground is computed, the fraction that is not captured is determined, and the average gpc on the ground is

calculated. To average the coating on the tree, a volume-weighted fraction coating is obtained:

$$\text{Fraction Coated} = \frac{\sum_{i=1}^{N} \sum_{j=1}^{M} P_{ij} V_{ij}}{\sum_{i=1}^{N} \sum_{j=1}^{M} V_{ij}}$$

where P_{ij} is the fraction coated in the i, jth cell,

and V_{ij} is the volume of the i, jth cell.

Salt Concentration Calculations

For each element of vegetation, the amount of retardant captured is known from the previous coating computations. To estimate the salt in the coating, it is necessary to have a concentration for the retardant. Four values, 1.0, 2.0, 3.0, and 4.0 pounds per gallon, were selected. These values enable calculation of the amount of salt at each level. The concentration can be calculated from the fuel loadings from the fine fuel description.

The concentration at each level is obtained, and the total concentration is the sum of this value and the natural salt concentrations in the fuels. The natural salt concentrations can be varied as input to the program. From Reference 2, the concept of η_r is applied to the coating at each fuel element. The particular equation for η_r is the following:

$$\eta_r = 1 - 1.699\, X^{(0.23)}$$

where X is $C + S_e$, i.e., the computed retardant concentration plus the natural salt concentration. For this example, the natural salt concentration was set at 0.01.

The program output contains the individual concentrations and the corresponding η_r. To summarize the effects of the salt on the vegetation, three average values for η_r have been defined. These average values have been constructed to measure the effects of the coating on reducing the potential fire spread. These averages are:

- Volume-weighted η_r
- Loading-weighted η_r averaged across the layer
- An importance value weighting.

The first average is simply the volume-weighted average:

$$\eta_r\,(\text{volume}) = \frac{\sum_{i=1}^{N}\sum_{j=1}^{M} V_{ij}(\eta_r)\ ij}{\sum_{i=1}^{N}\sum_{j=1}^{M} V_{ij}}$$

where V_{ij} is the volume of i, j element and $(\eta_r)_{ij}$ is the calculated value of η_{ij}.

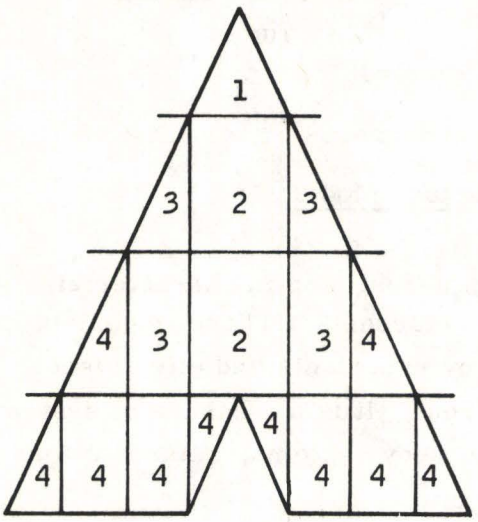
This gives the simplest average to interpret because it assigns only a volume weight to the computed average.

The second average is the weighting that expresses the importance of fuel loadings in the layers. This average is:

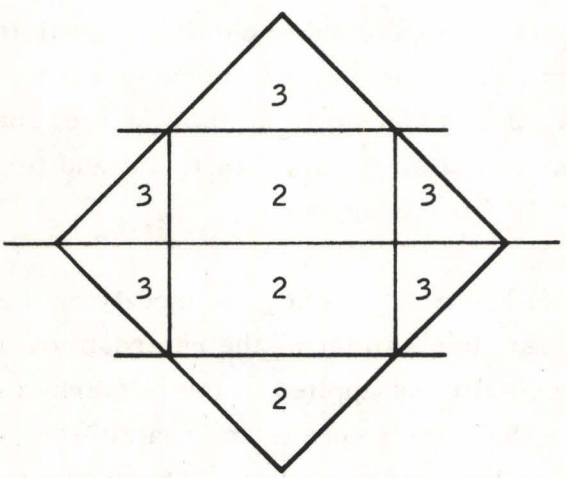
$$\eta_r(\text{load}) = \sum_{i=1}^{N} W_{oi} \left(\frac{\sum_{j=1}^{M} V_{ij}(\eta_r)ij}{\sum_{j=1}^{M} V_{ij}} \right)$$

The bracketed term is the layer volume-weighted η_r, and this average assigns greater importance to the heavy fuel loadings.

The final average is an arbitrary assignment of weight values to the elements of the vegetation. For the Douglas Fir tree, the weights (W_{ij}) are:



For chaparral, the weights (W_{ij}) are:



These weighted values are then averaged:

$$\eta(\text{weight}) = \frac{\sum_{i=1}^{N} \sum_{j=1}^{M} W_{ij} V_{ij} (\eta_r)_{ij}}{\sum_{i=1}^{N} \sum_{j=1}^{M} (W_{ij} V_{ij})}$$

Application of the Capture Model

The capture model is a first step in characterizing several important factors in aerial delivery of retardants. These important factors include uniformity of fine fuel coatings by retardants and effectiveness of these coatings in modifying the fire threat. It is a measure of system effectiveness that can be used in evaluating delivery systems, retardant formulations, and the tactical application of retardants.

This model has been useful during the High-Altitude Retardant Delivery contract in separating the aerial delivery phase from treatment of the fine fuels. In Appendices A and B, effectiveness of retardants on the Douglas Fir tree and chaparral stands are examined in detail. Sensitivity studies involving the film thickness parameter, the application rate, and the salt concentration are presented. These studies characterize the fine fuel coating by retardants, and the conclusions are of such importance that additional theoretical/experimental studies merit consideration.

For effectiveness of retardant delivery in modifying the fire threat, the capture model is a mechanism for estimating the retardant damping coefficient. The retardant damping coefficient applied to the Rothermel Fire Spread Model gives the change in the rate of spread and reaction intensity, which are the two parameters useful in laboratory studies. These parameters can be related to Byram's Intensity, which is a traditional measure that has been used to describe real-world fires.

The two basic equations for the Rothermel Fire Spread Model are:

$$R = I_R \xi \frac{(1 + \varphi_w + \varphi_s)}{\rho_b e Q_{ig}}, \text{ rate of spread (feet per minute)}$$

and

$$I_r = \Gamma' w_\eta h \eta_m \eta_s, \text{ Reaction Intensity (BTU - feet}^2\text{/minute)}$$

where ξ is the propagating flux ratio

φ_w is the wind coefficient

φ_s is the slope factor

ρ_b oven dry bulk density

e is the effective heating number

Q_{ij} is the heat of preignition

Γ' is the optimum reaction velocity

w_η is the net fuel loading

h is fuel particle low heat content

η_m is the moisture damping coefficient

η_s is the mineral damping coefficient.

η_s is the mineral damping coefficient in the ratio of the rate of spread in natural fuels to the rate of spread with the fuels depleted of all effective minerals. To evaluate retardants, Rothermel and Philpot[2] define a similar coefficient η_r to account for the effect of retardant salt concentration on rate of fire spread. This coefficient η_r can be estimated from the data of George and Blakey[10], and Rothermel and Philpot showed that η_r could be represented by a general power function of the form:

$$\eta_r = 1 - k\,[S_{(e+r)}]^{\eta},$$

where S (e + r) is the effective retardant concentration

$$S\,(e + r) = S_e + S_r$$

when S_e and S_r are the natural mineral and retardant concentrations.

Rothermel has shown that Byram's Intensity can be related to the Rothermel Fire Spread Model as follows:

I_B = R w h (BTU – feet/minute)

I_B = Byram's Intensity

R = Rate of Spread (feet/minute)

w = Available Fuel (lb/ft^2)

h = Heat content (BTU/lb)

It may also be calculated from reaction intensity (I_R) given by Rothermel:[4]

$$I_B = I_R\,D$$

where I_R = Reaction Intensity (BTU – $feet^2$/minute)

D = Flame depth.

Flame depth can be calculated by:

$$D = R\,t_r$$

where R = rate of spread (fps)

t_r = residence time (seconds).

Anderson[5] shows that the residence time is related to fuel particle diameter by:

$$t_r = 8d$$

d = particle diameter in inches.

For fuel models it is known that $d = \frac{4}{\sigma}$ (3)

where σ is surface to volume ratio. The characteristic σ of a mixed-size array is given by Rothermel as $\tilde{\sigma}$, the mean value weighted by surface area, substituting

$$D = (R)\,(8)\,\left(\frac{4}{\tilde{\sigma}}\right)\,(12)$$

$$= \frac{384\,R}{\tilde{\sigma}}$$

and

$$I_B = \frac{384\,R\,I_R}{\tilde{\sigma}} \quad \text{(BTU - feet/minute)}$$

$$= \frac{6.4\,R\,I_R}{\tilde{\sigma}} \quad \text{(BTU - fps)}$$

The change in Byram's Intensity due to retardant application is now relatable to the retardant damping coefficient change. The before and after reaction intensity and spread rates are:

$$R_2 = R_1\,\frac{\eta_{r_2}}{\eta_{r_1}} \quad \text{and} \quad I_{R_2} = I_{R_1}\,\frac{\eta_{r_2}}{\eta_{r_1}}$$

where the subscripts 1 and 2 denote the reaction intensity, retardant damping coefficient and spread rates before and after treatment.

It follows that Byram's Intensity is given by:

$$I_{B_2} = I_{B_1}\,\left(\frac{\eta_{r_2}}{\eta_{r_1}}\right)^2$$

CONCLUSION

The results discussed above yield some distinct surprises that should be subjected to future evaluation. This study has shown the following:

- Fir tree crown allows more retardant to pass through than expected.
- The chaparral data show less porosity than expected, although some of the fuels in the mixed brush field, like the Chamise, have characteristics that could lead to the conclusions of the model.
- These representative fuel models applied to the capture technique provide a range of vertical fuel situations that must be accommodated by an effective retardant delivery system.
- Application of the capture model, fine fuels description, Rothermel Fire Spread Model, and Byram's Intensity to retardant application provides a measure of effectiveness for aerial delivery.

APPENDIX A

DOUGLAS FIR DATA

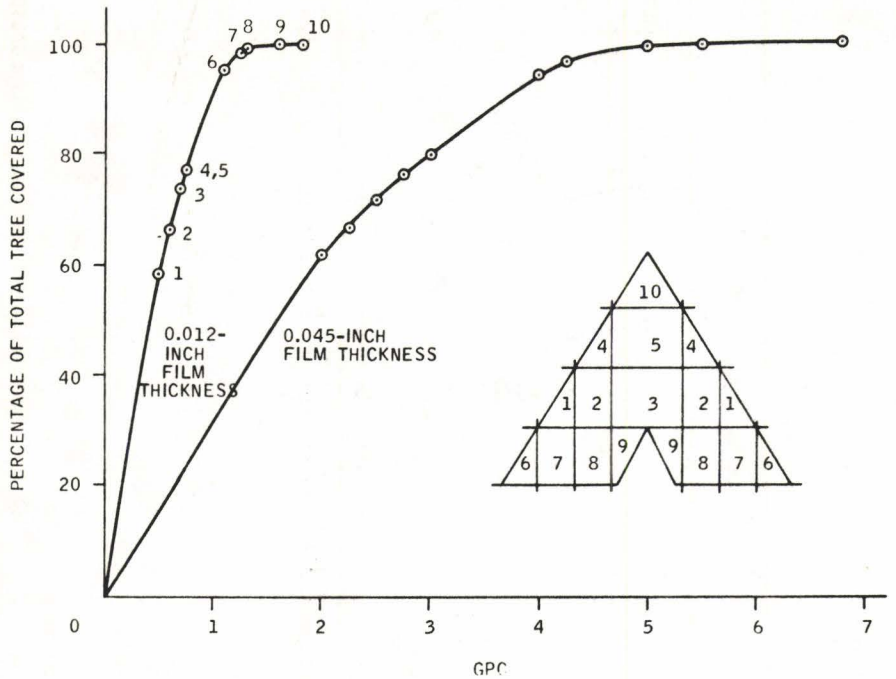


Figure A1. Percent Covered versus Application Rate (Two Film Thicknesses)

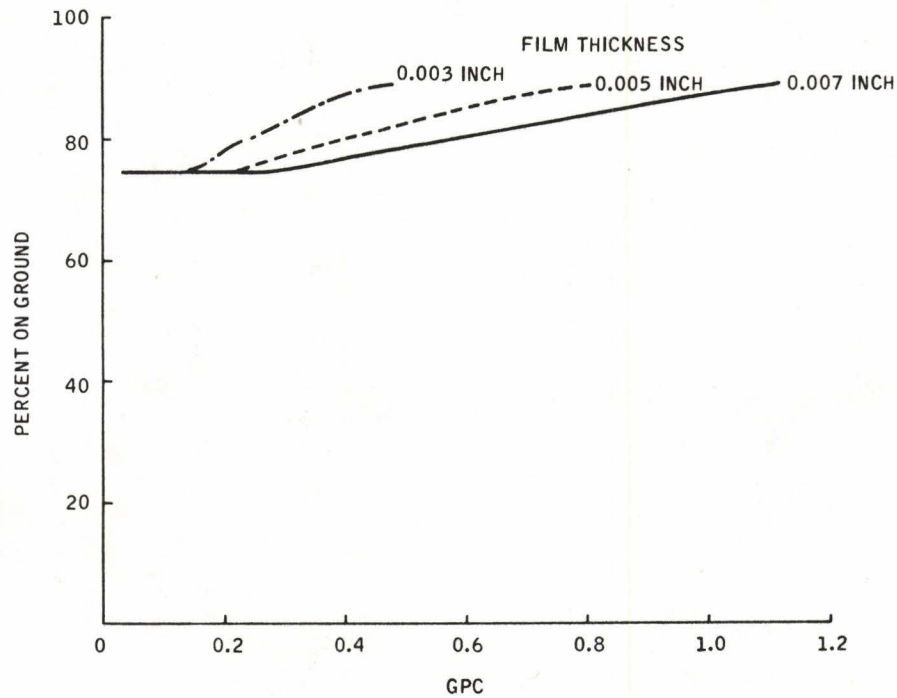


Figure A2. Percent on Ground versus Application Rate (Three Film Thicknesses)

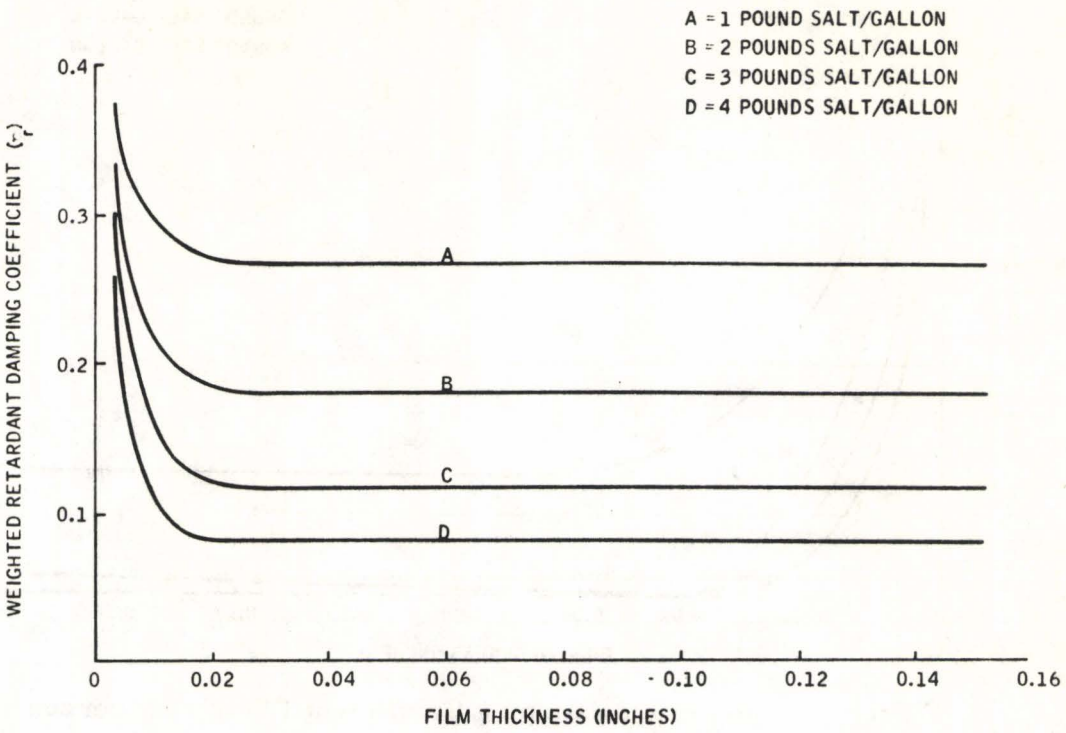


Figure A3. Retardant Damping Coefficient (Weighted) versus Film Thickness, 1 gpc

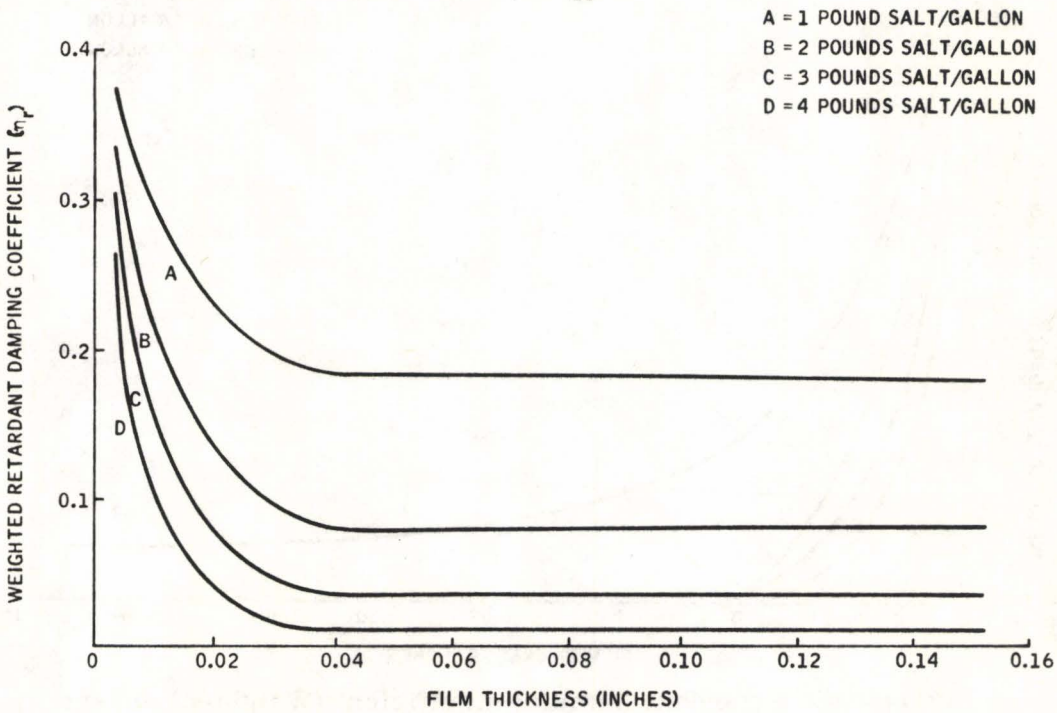


Figure A4. Retardant Damping Coefficient (Weighted) versus Film Thickness, 2 gpc

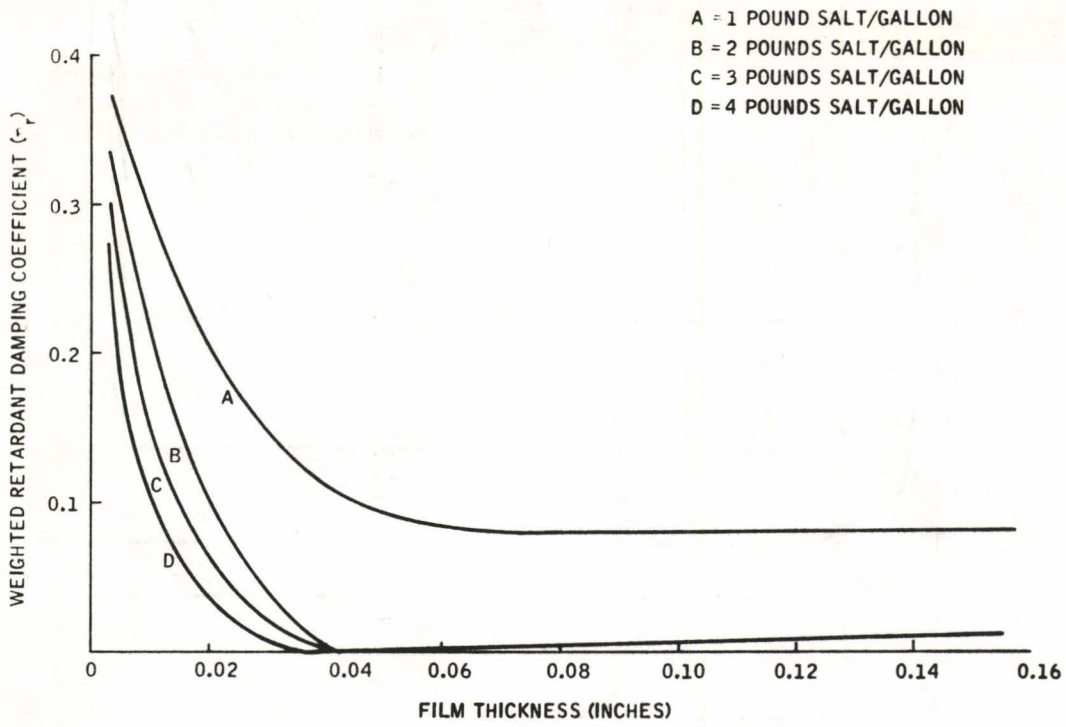


Figure A5. Retardant Damping Coefficient (Weighted) versus Film Thickness, 4 gpc

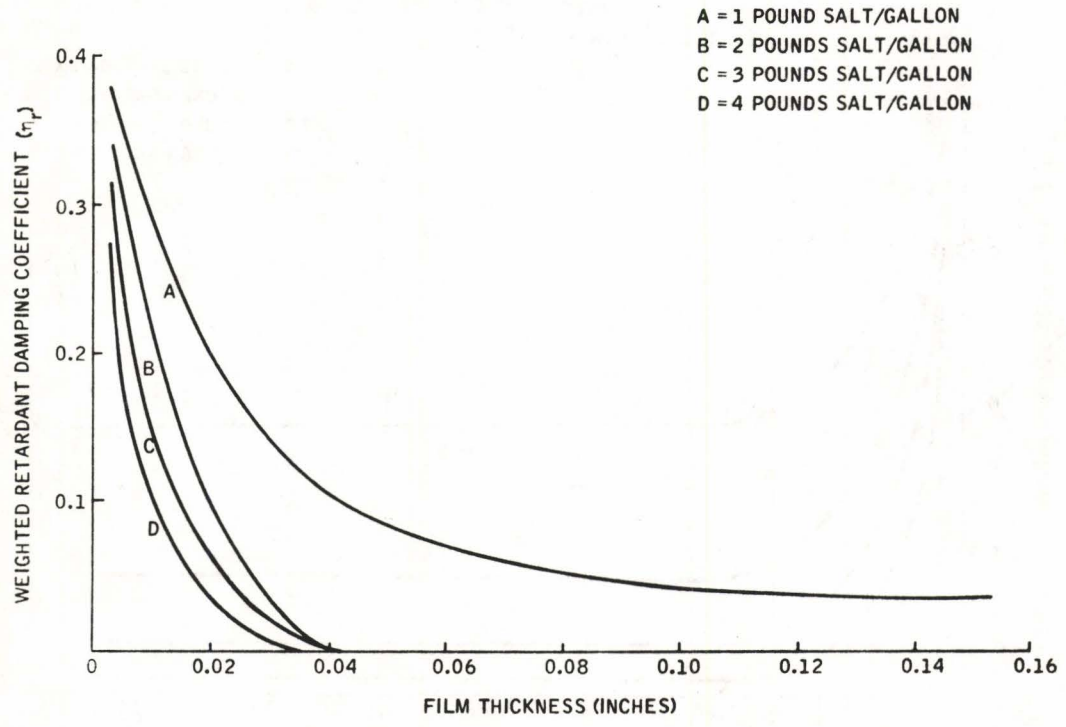


Figure A6. Retardant Damping Coefficient (Weighted) versus Film Thickness, 6 gpc

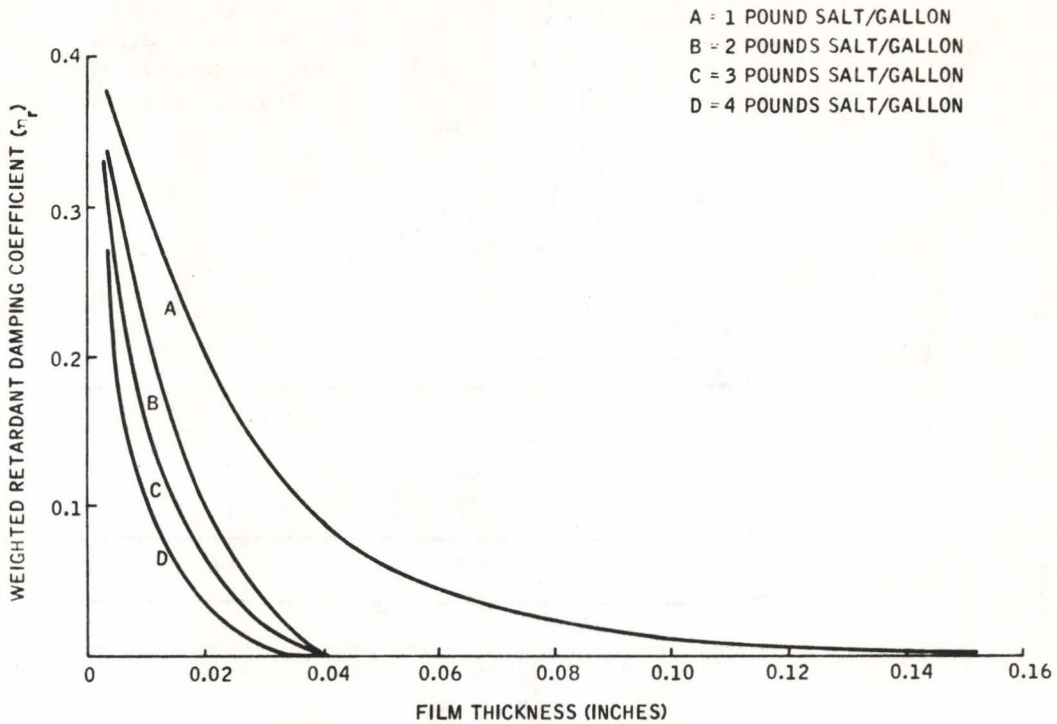


Figure A7. Retardant Damping Coefficient (Weighted) versus Film Thickness, 10 gpc

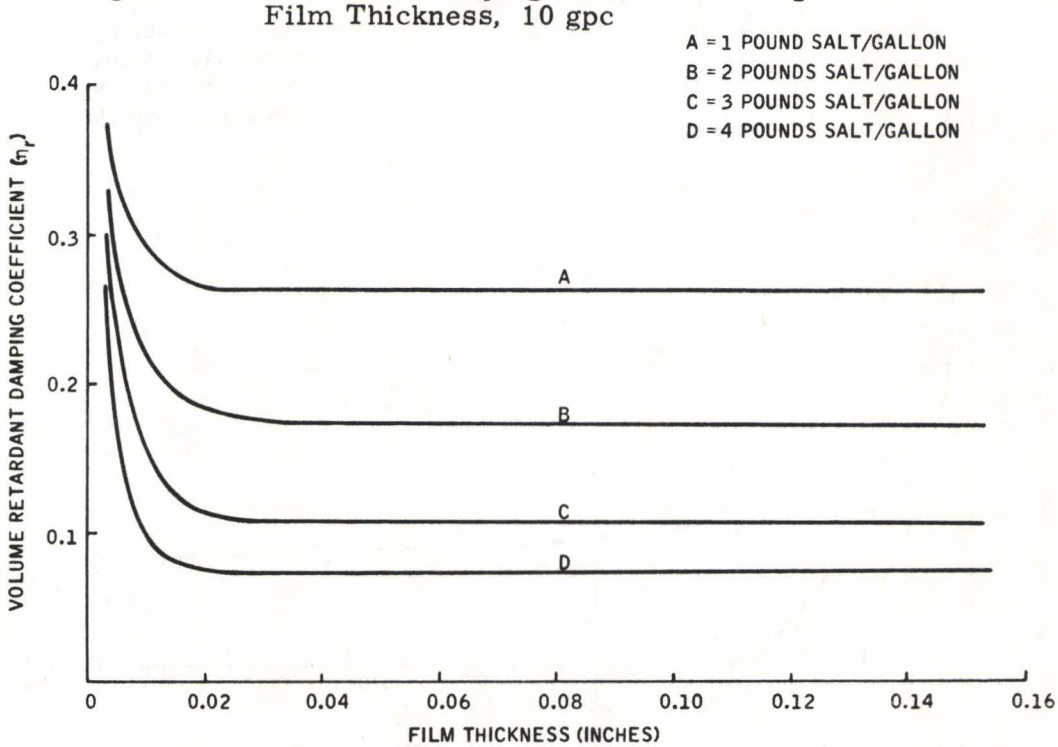


Figure A8. Retardant Damping Coefficient (Volume) versus Film Thickness, 1 gpc

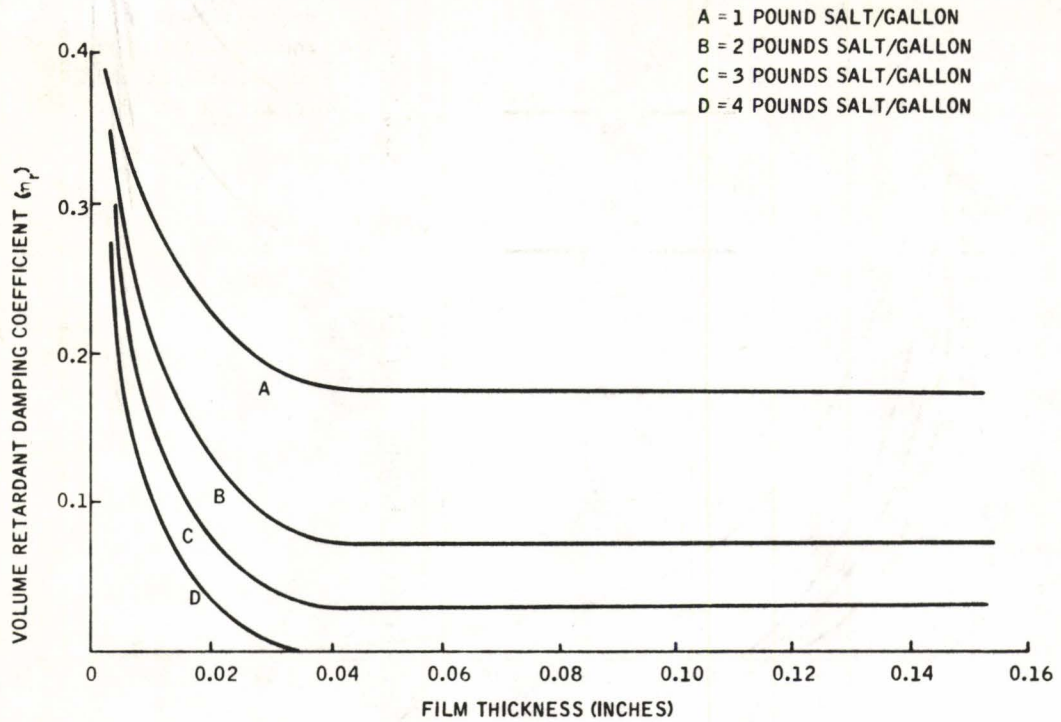


Figure A9. Retardant Damping Coefficient (Volume) versus Film Thickness, 2 gpc

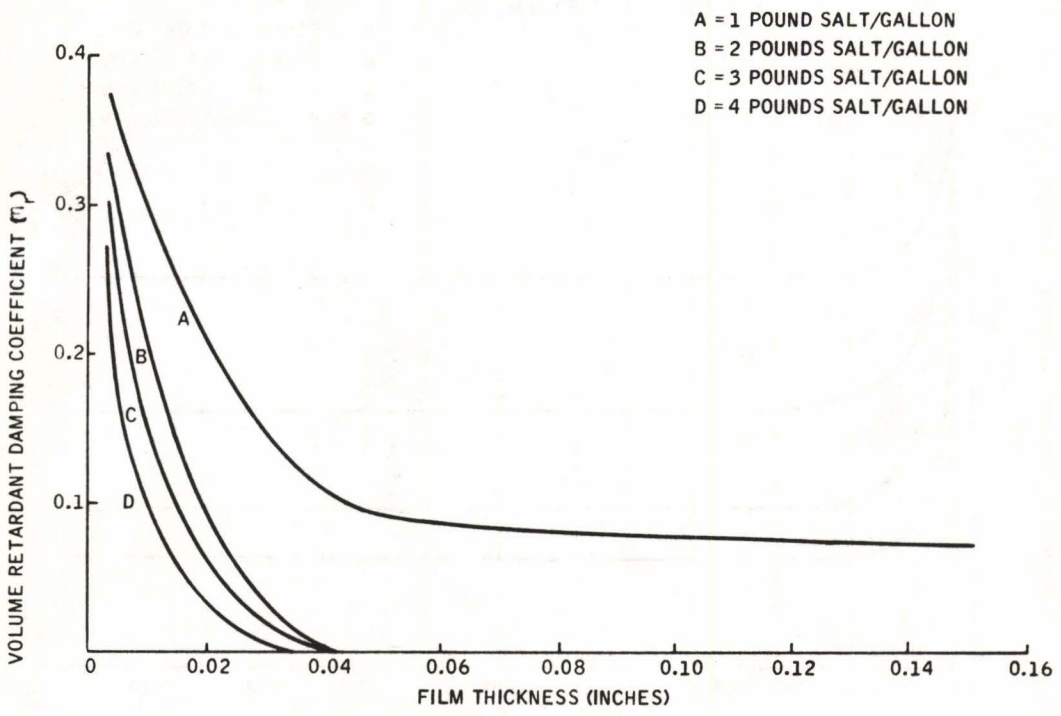


Figure A10. Retardant Damping Coefficient (Volume) versus Film Thickness, 4 gpc

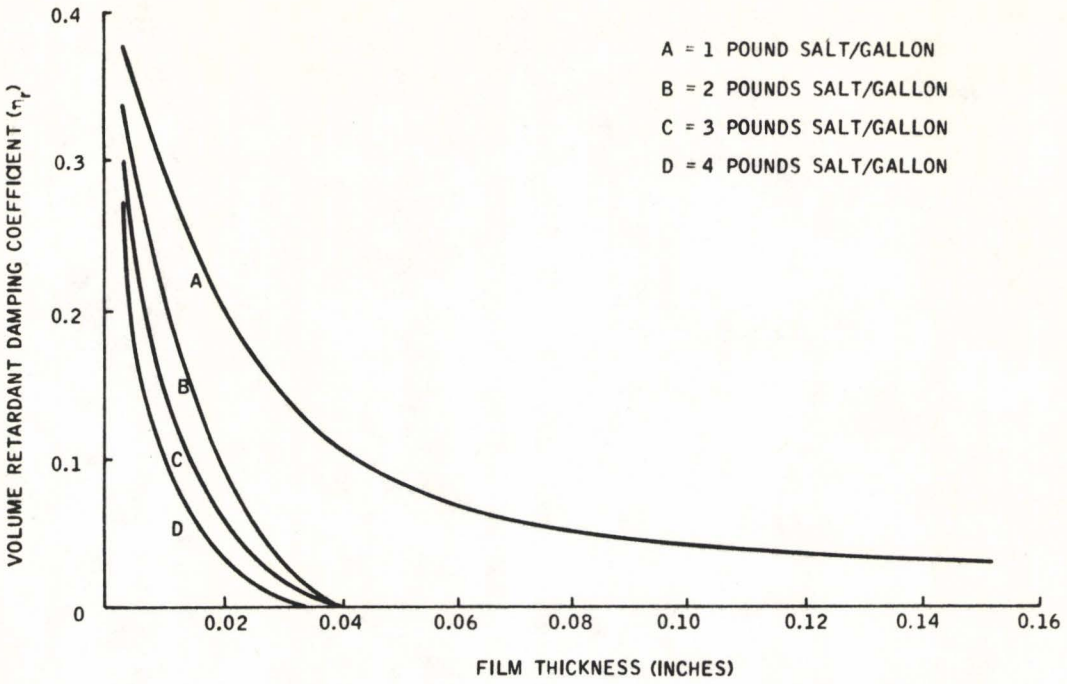


Figure A11. Retardant Damping Coefficient (Volume) versus Film Thickness, 6 gpc

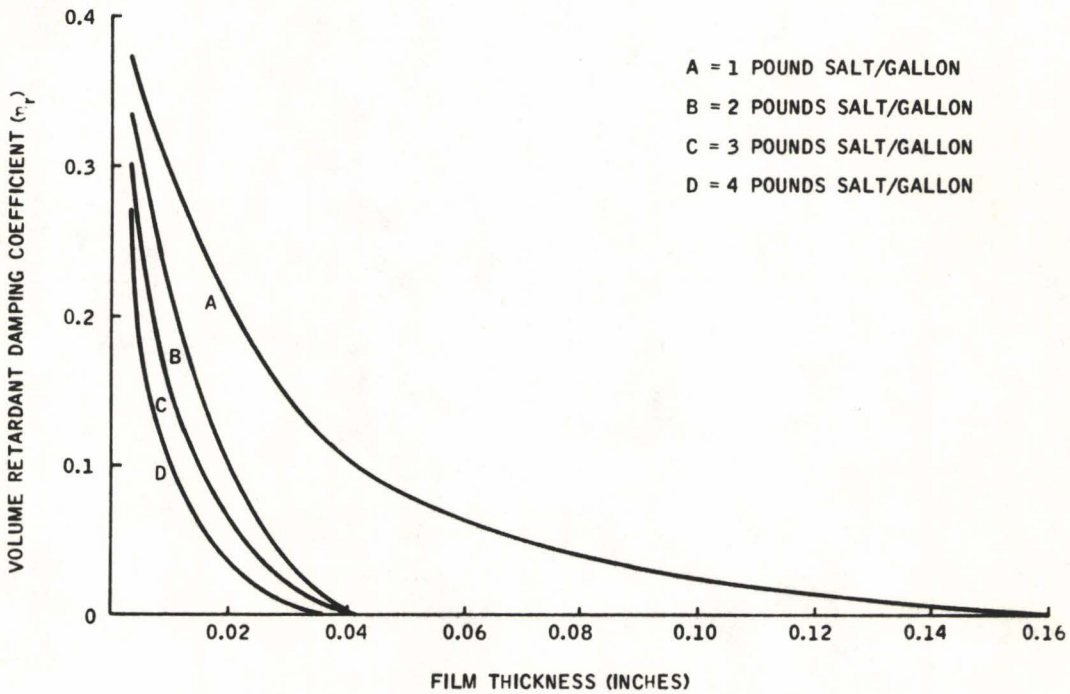


Figure A12. Retardant Damping Coefficient (Volume) versus Film Thickness, 10 gpc

APPENDIX B

CHAPARRAL BUSH DATA

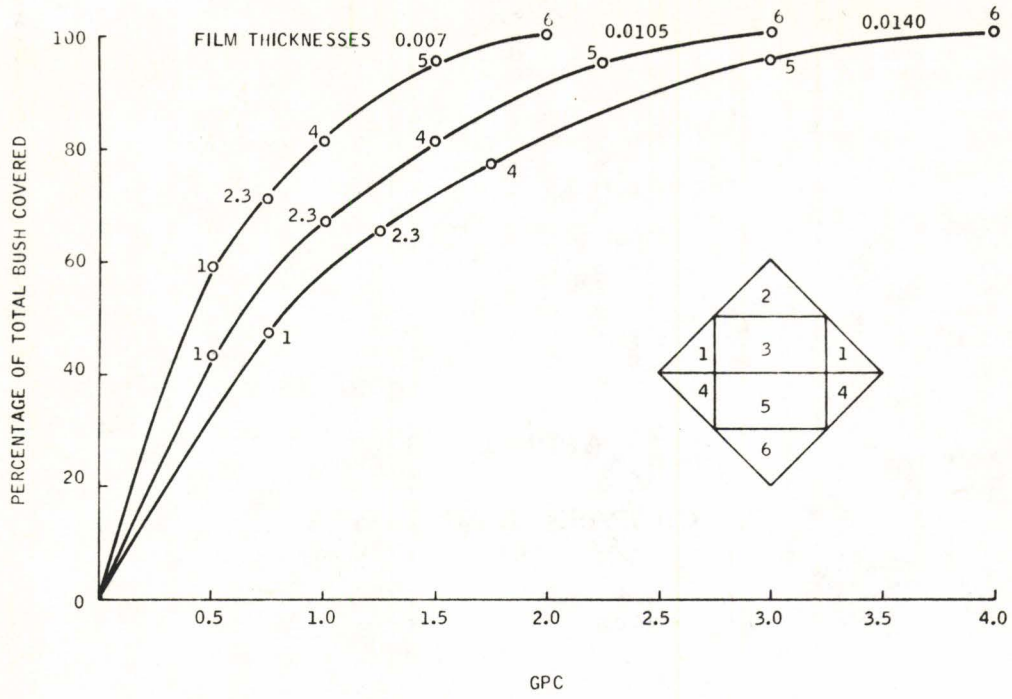


Figure B1. Percent Covered versus Application Rate (Three Film Thicknesses)

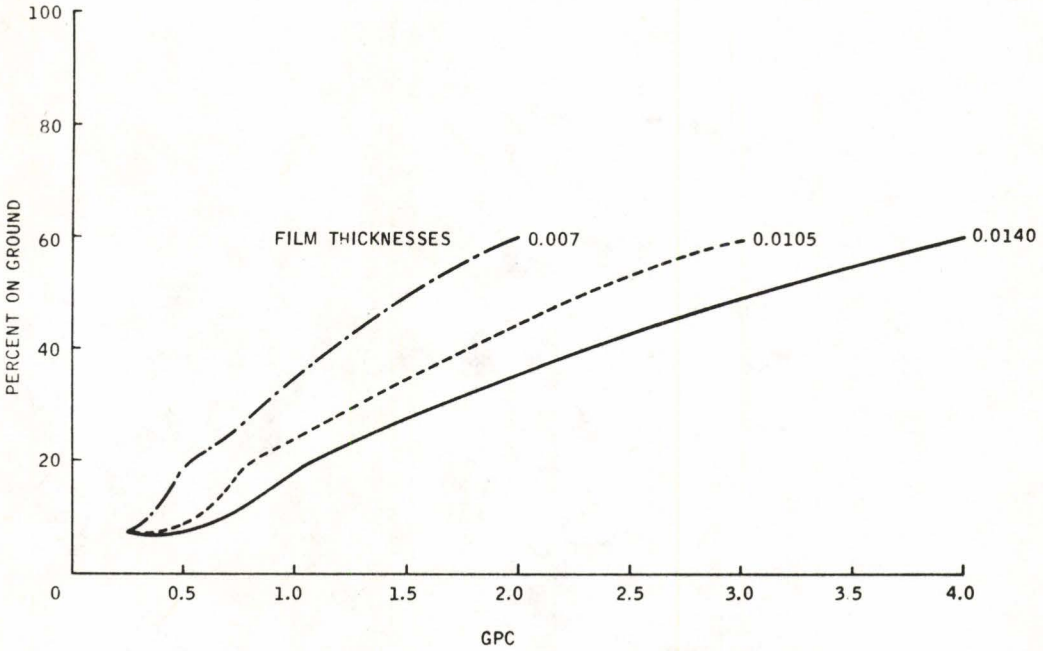


Figure B2. Percent on Ground versus Application Rate (Three Film Thicknesses)

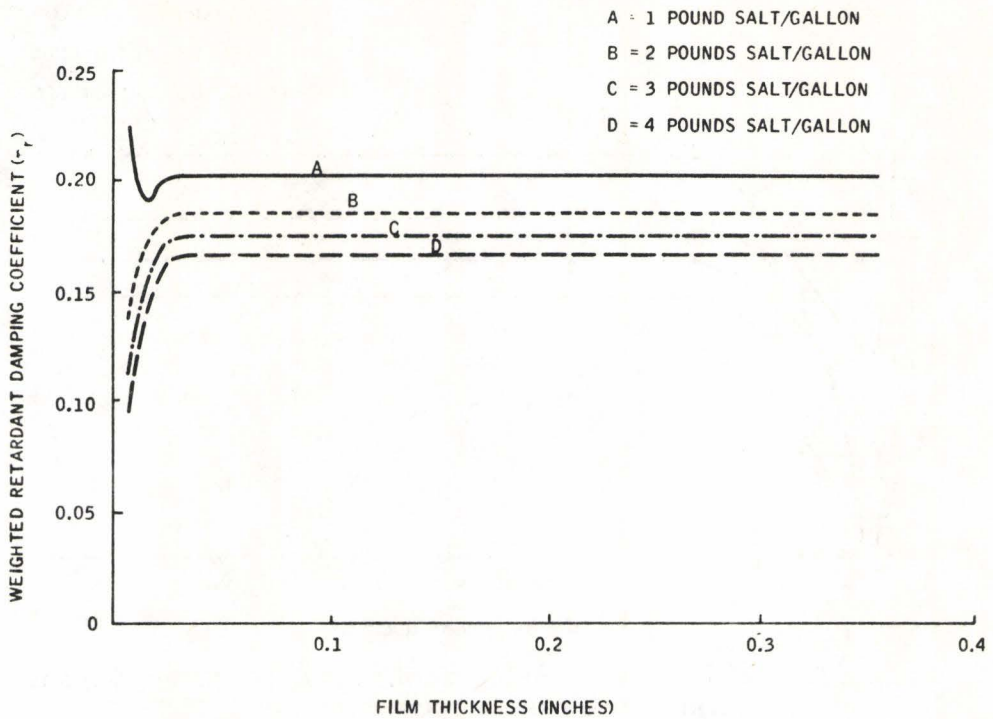


Figure B3. Retardant Damping Coefficient (Weighted) versus Film Thickness, 1 gpc

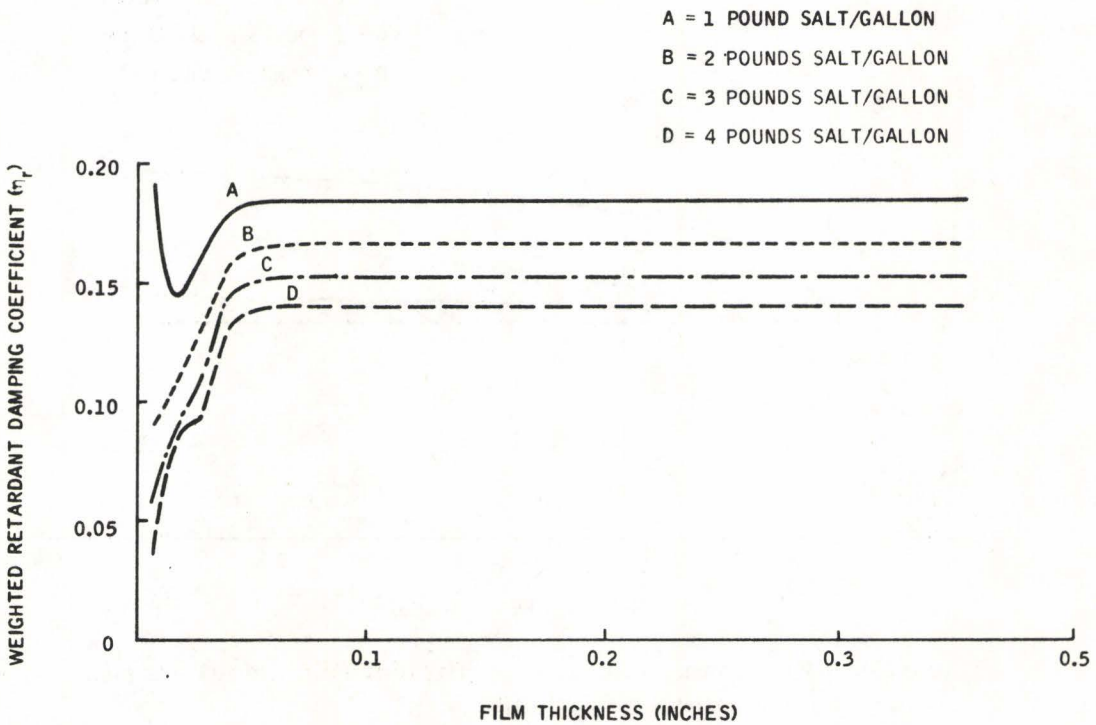


Figure B4. Retardant Damping Coefficient (Weighted) versus Film Thickness, 2 gpc

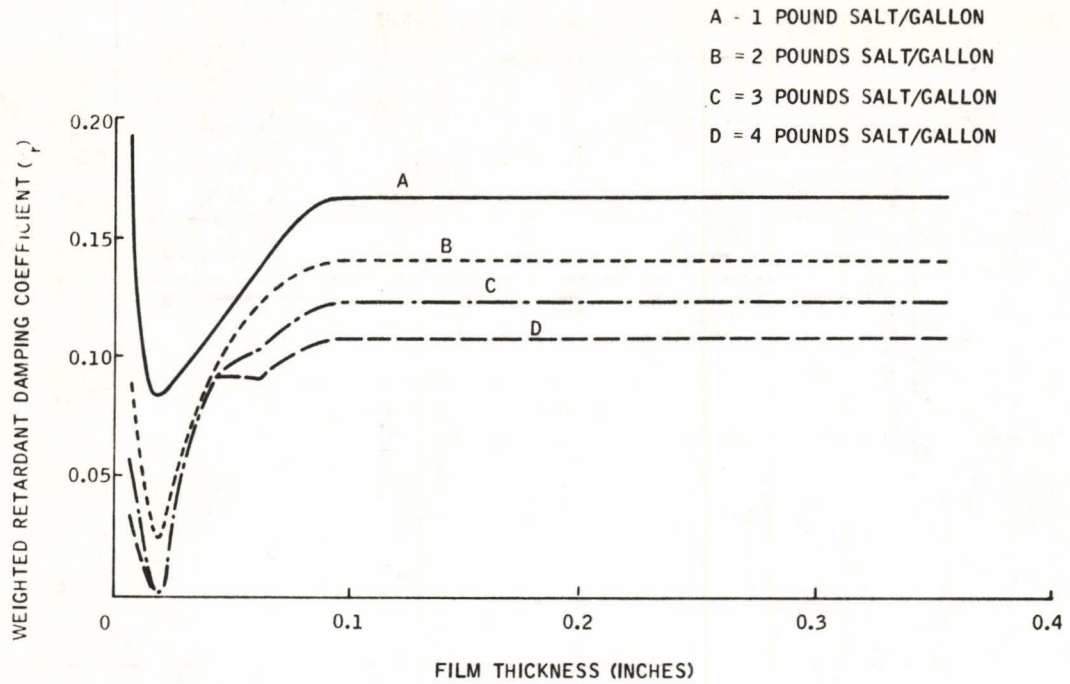


Figure B5. Retardant Damping Coefficient (Weighted) versus Film Thickness, 4 gpc

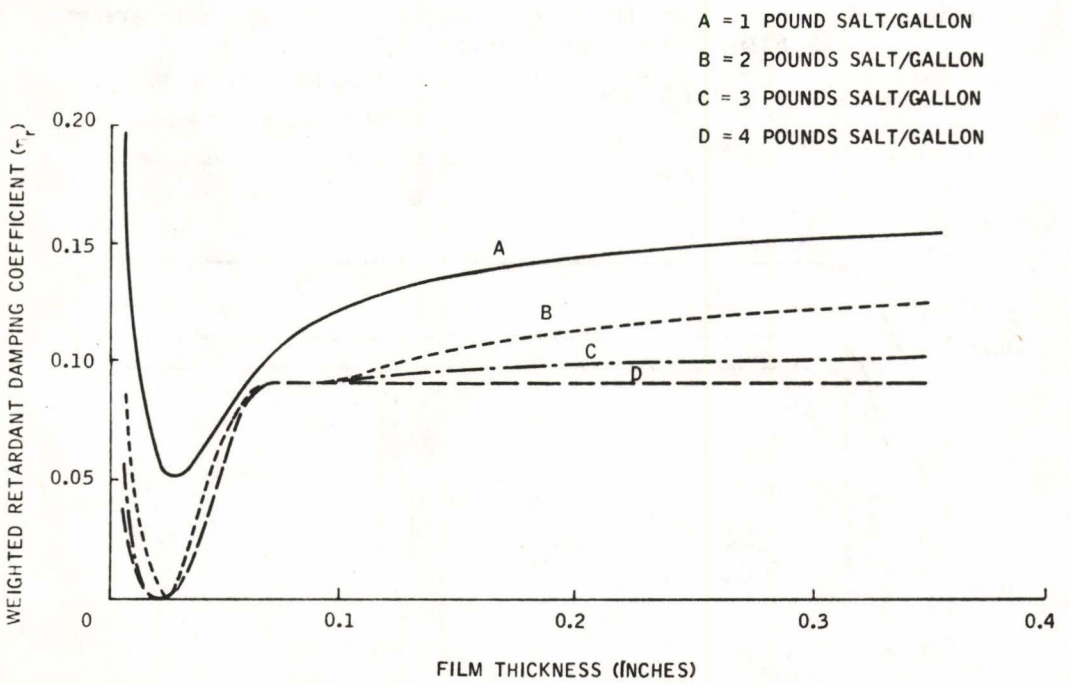


Figure B6. Retardant Damping Coefficient (Weighted) versus Film Thickness, 6 gpc

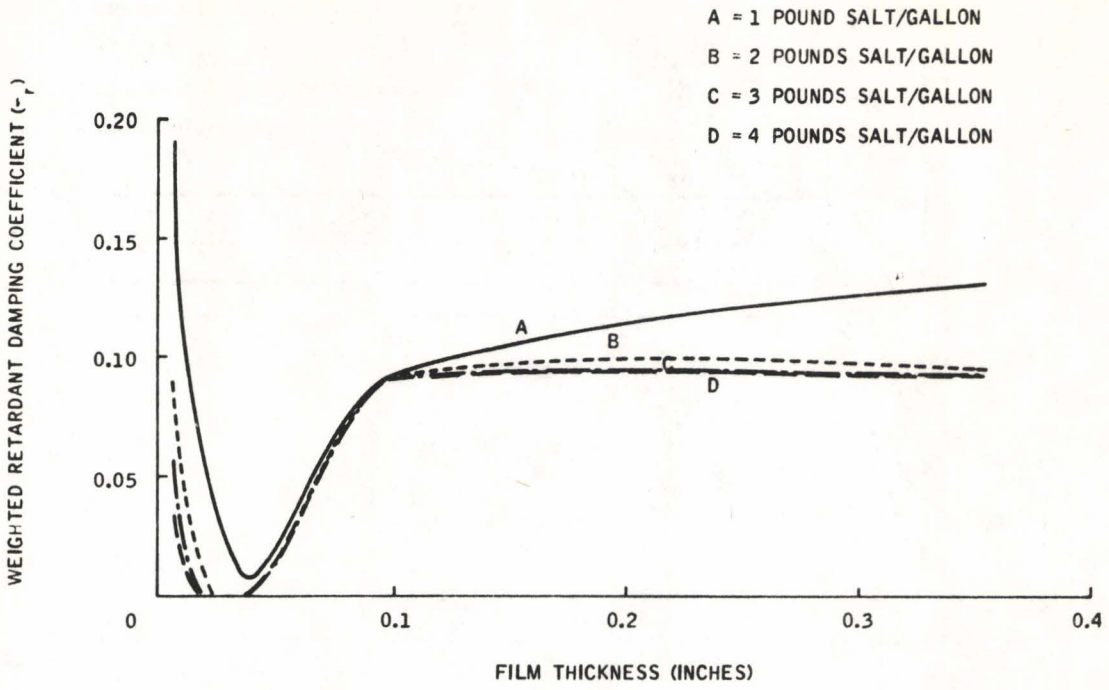


Figure B7. Retardant Damping Coefficient (Weighted) versus Film Thickness, 10 gpc

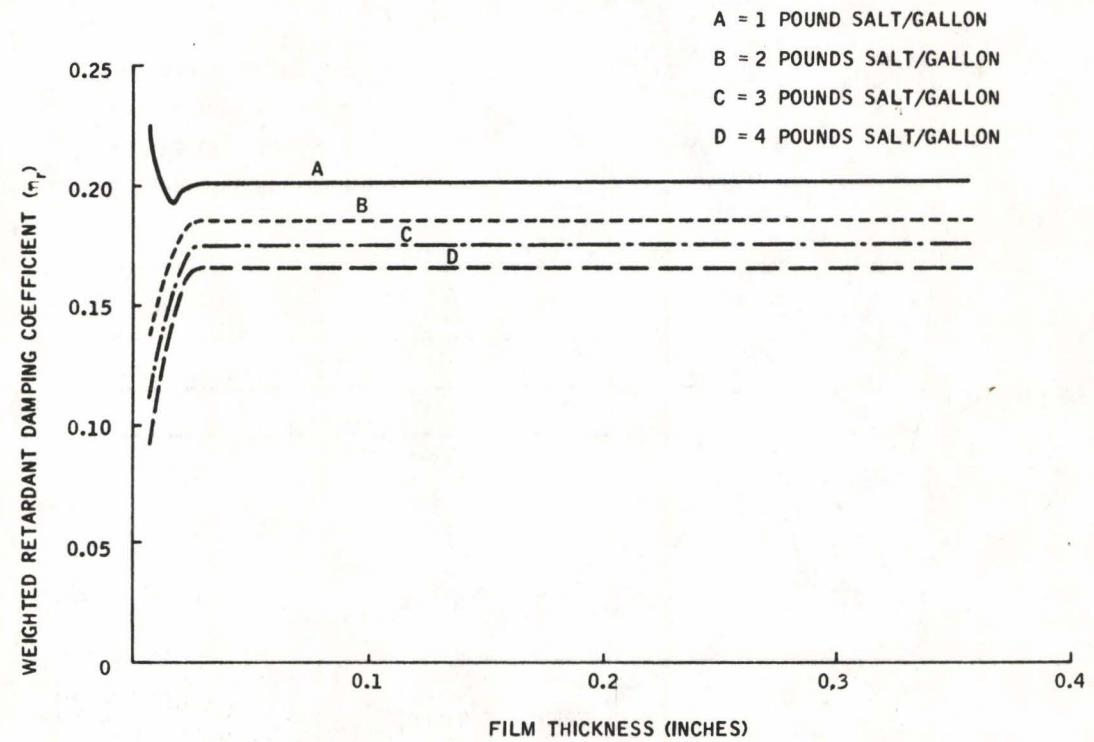


Figure B8. Retardant Damping Coefficient (Volume) versus Film Thickness, 1 gpc

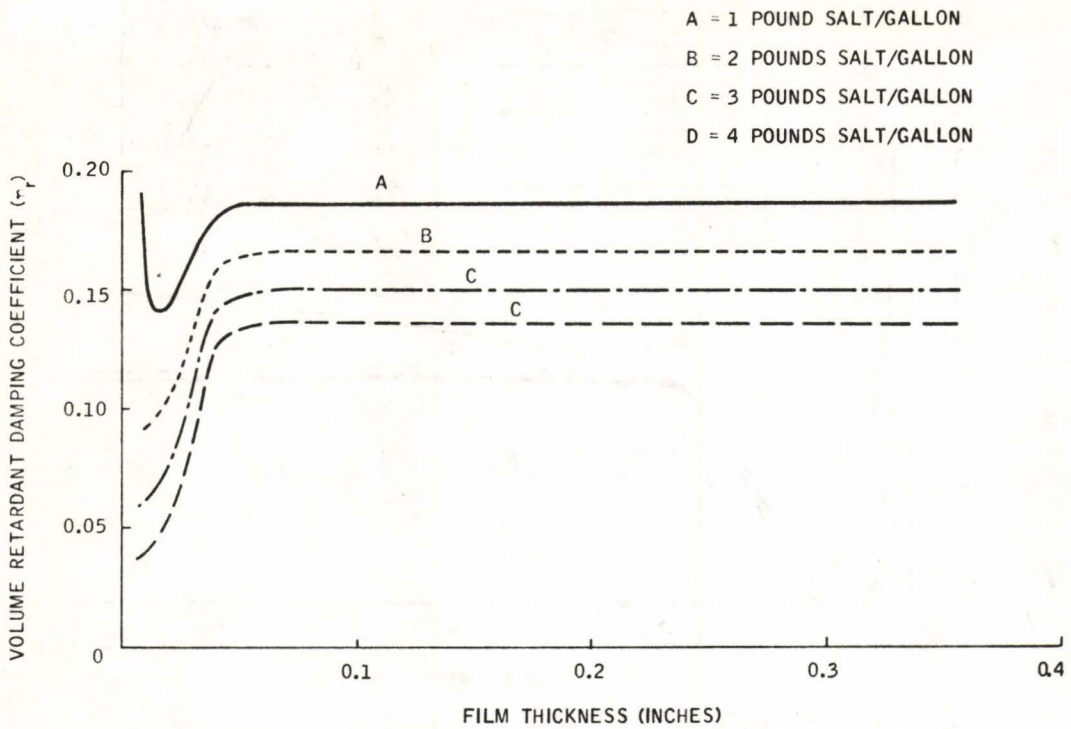


Figure B9. Retardant Damping Coefficient (Volume) versus Film Thickness, 2 gpc

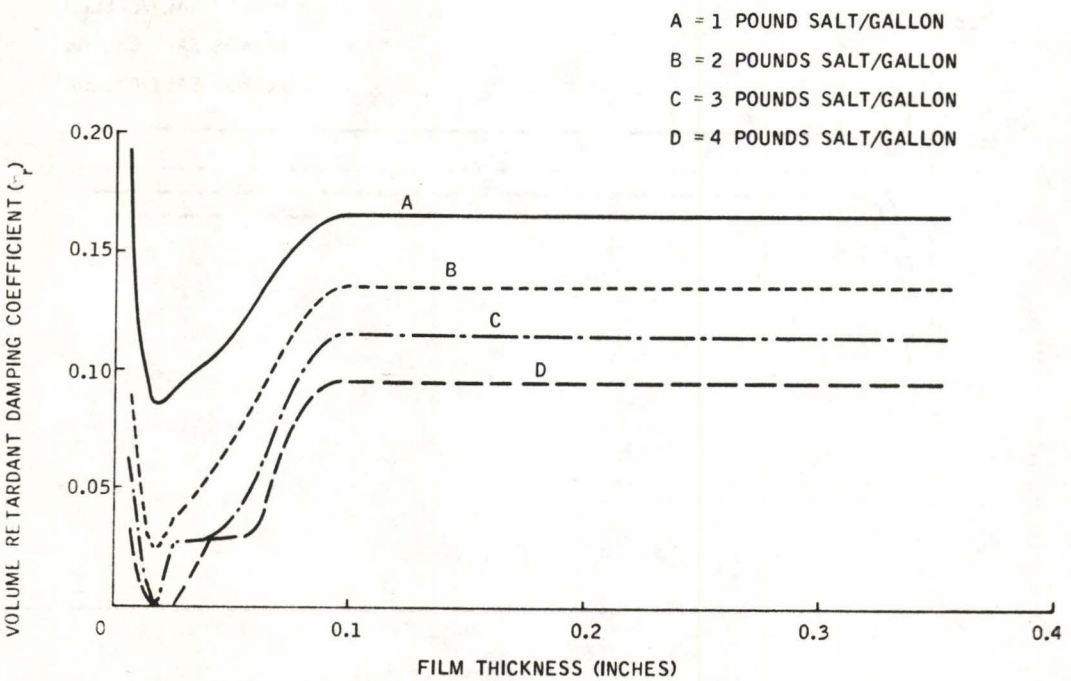


Figure B10. Retardant Damping Coefficient (Volume) versus Film Thickness, 4 gpc

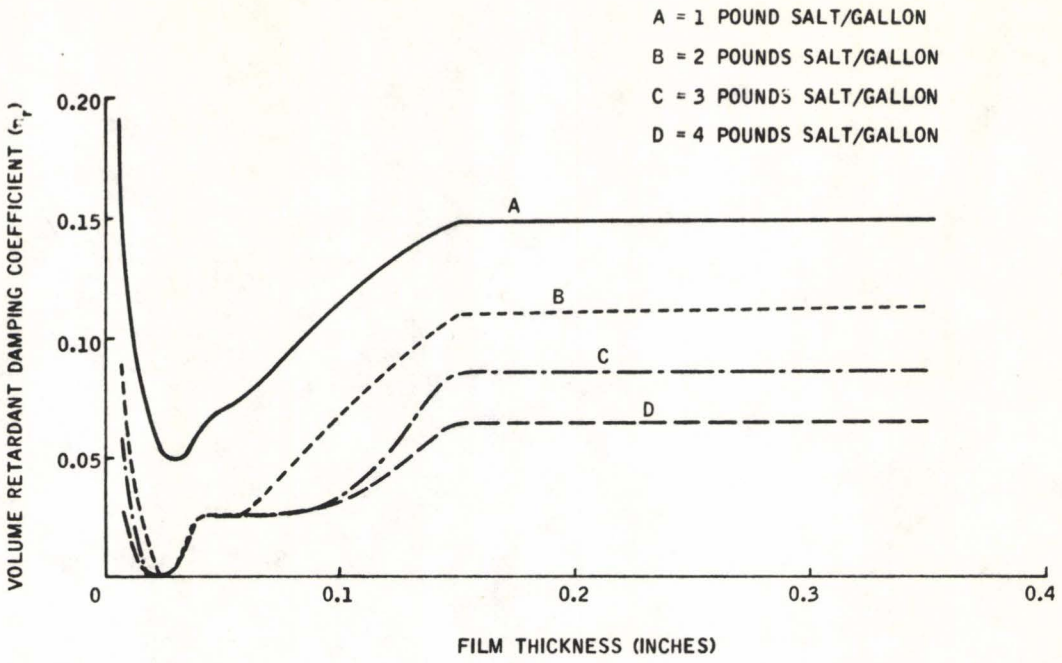


Figure B11. Retardant Damping Coefficient (Volume) versus Film Thickness, 6 gpc

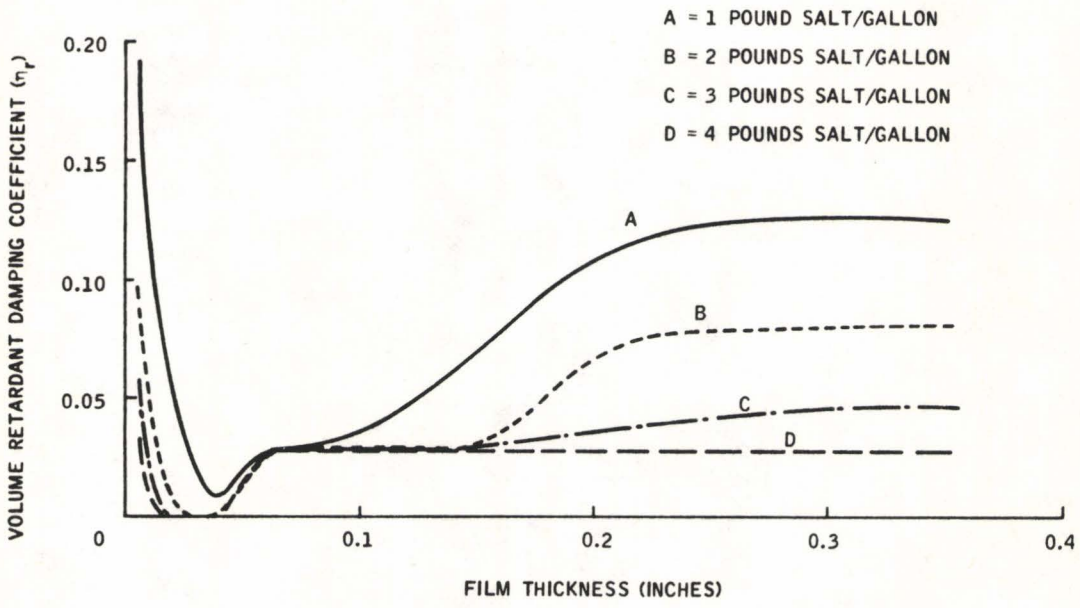


Figure B12. Retardant Damping Coefficient (Volume) versus Film Thickness, 10 gpc

APPENDIX C

RELATIONSHIP OF FILM THICKNESS TO RHEOLOGICAL PROPERTIES

SUMMARY

Films of fire retardants on fuels can decrease in thickness with time due to "running" brought on by fluid flow. This study presents a quick look at the equations of the process for a simple model. After a sufficiently long time (many minutes), to a first approximation the thickness of the film varies with the square root of the viscosity and is independent of the initial film thickness. Such films are subjected to evaporation that is not considered herein.

THE MODEL

Figure C1 presents the film model.

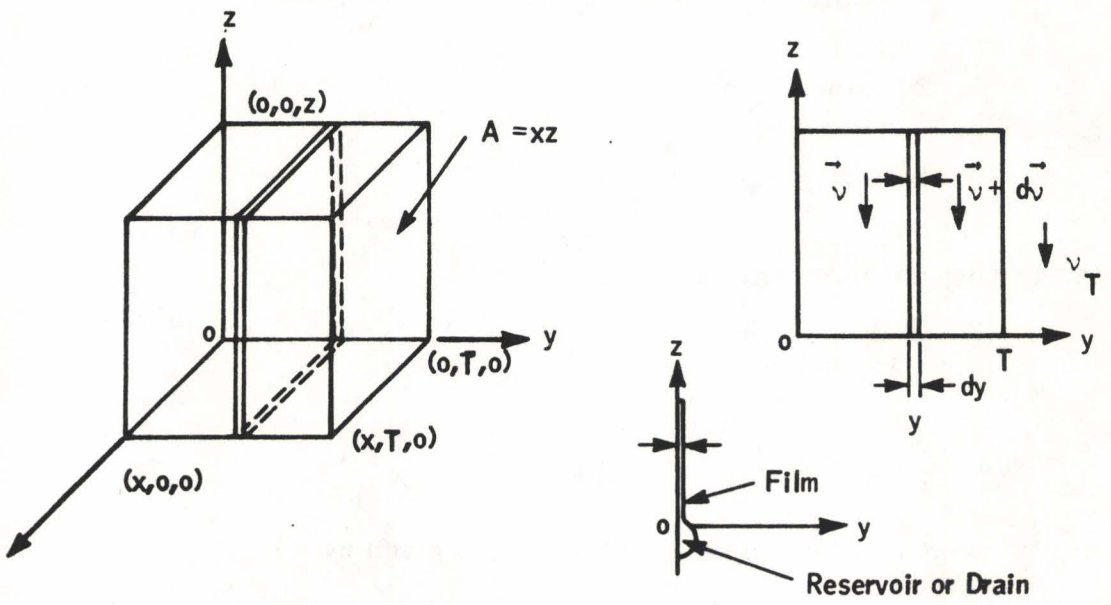


Figure C1. A Film of Area A and Thickness on a Vertical Surface Subjected to Thinning by Fluid Flow

The shear stress on the liquid element Ady is given by

$$\frac{F}{A} = \rho_\ell (T-y)a, \ (\text{dynes/cm}^2) \tag{1}$$

where

F = force (weight) of the liquid causing the shear stress on the element (dynes)

A = area of liquid film (cm^2)

ρ_ℓ = density of the liquid film (g/cm^3)

T = thickness of the film (cm)

a = acceleration due to gravity = 980.66 (cm/sec^2)

ν = velocity (cm/sec).

From the definition of viscosity

$$\frac{F}{A} = \mu \frac{d\nu}{dy} \ (\text{dynes/cm}^2) \tag{2}$$

where

μ = the coefficient of viscosity (poise = $\frac{\text{dyne--sec}}{\text{cm}^2}$).

Combining Equations 1 and 2 gives

$$(T-y)dy = \frac{\mu}{a\rho_\ell} \, d\nu \ (\text{cm}^2). \tag{3}$$

Integrating Equation 3 gives

$$\int_0^y (T-y)\,dy = \frac{\mu}{a\rho_\ell} \int_0^\nu d\nu \tag{4a}$$

$$Ty - \frac{y^2}{2} = \frac{\mu\nu}{a\rho_\ell} \tag{4b}$$

or the speed as a function of y in the film is given by

$$\nu(y) = \frac{a\rho_\ell}{\mu} \left(Ty - \frac{y^2}{2}\right) \text{(cm/sec)}. \tag{5}$$

When the speed is that at the surface of the film, Equation 5 becomes

$$\nu_T = \frac{a\rho_\ell}{\mu} \frac{T^2}{2} \text{ (cm/sec).} \tag{6}$$

The loss of volume with time from the film will be considered to be that flowing below the xy plane. The volume flow rate, $\frac{dV}{dt}$, is obtained using Equation 5 as

$$\frac{dV}{dt} = - \int_o^T \nu(y) x \, dy, \quad x \neq x(y) \tag{7}$$

$$= \int_o^T \frac{xa\rho_\ell}{\mu} (Ty - \frac{y^2}{2}) \, dy$$

$$= - \frac{xa\rho_\ell}{\mu} (\frac{T^3}{2} - \frac{T^3}{6})$$

$$= - \frac{xa\rho_\ell}{\mu} \frac{T^3}{3} \text{ (cm}^3\text{/sec).}$$

But from $V = AT$

$$\frac{dV}{dt} = A \frac{dT}{dt}. \tag{8}$$

Integrating Equation 7 with Equation 8 gives

$$\int_{T_o}^T \frac{dT}{T3} = \int_o^t - \frac{xa\rho_\ell}{3A\mu} \, dt = \int_o^t - \frac{a\rho_\ell}{3Z\mu} \, dt \tag{9a}$$

$$T^{-2} = T_o^{-2} + \frac{2a\rho_\ell}{3Z\mu} \text{ (cm}^{-2}\text{)} \tag{9b}$$

$$T = \frac{T_o}{\sqrt{1 + \frac{2a\rho_\ell T_o^2}{3Z\mu} t}} \quad (cm) \tag{9c}$$

If the film makes an angle θ with the vertical, $\theta = 0$ being vertical, then Equation 9c becomes

$$T = \frac{T_o}{\sqrt{1 + \frac{2(a \cos \theta)\rho_\ell T_o^2}{3Z\mu} \cdot t}} \quad (cm) \tag{10}$$

Two approximations to Equation 10 are

$$T \cong T_o \left(1 - \frac{(a \cos \theta \rho_\ell T_o^2}{3Z\mu} \cdot t\right), \qquad \frac{2(a \cos \theta)\rho_\ell T_o^2}{3Z} \cdot t \ll 1 \tag{11}$$

and

$$T \cong \left(\frac{3Z\mu}{2(a \cos \theta)\rho_\ell} \cdot \frac{1}{t}\right)^{1/2}, \qquad \frac{2(a \cos \theta)\rho_\ell T_o^2}{3Z\mu} \cdot t \gg 1 \tag{12}$$

OTHER CONSIDERATIONS

This analysis considers the effect of surface tension to be negligible. Surface tension (actually interfacial tension) should be considered when it is large and when A is small, e.g., droplets of water on waxed surfaces. The analysis considers the film to drain, but not to admit additional liquid. In the process of draining, the film will take on a wedge-shaped thickness profile that is simplified to uniform thickness in the model.

Examples

Consider as an example these values which might* be reasonable for water:

$$T_o = 0.010 \text{ (inch)} \times 2.54 \text{ (cm/in)} = 2.54 \times 10^{-2} \text{ (cm)} \tag{13}$$

$$\rho_\ell = 1 \text{ (g/cm}^3\text{)}$$

$$\mu = 0.01 \text{ (poise)}$$

$$a = 980.66 \text{ (cm/sec}^2\text{)}$$

$$\theta = 0 \text{ (radians)}$$

$$Z = 10 \text{ (cm).}$$

Then

$$\frac{2(a \cos \theta) \rho_\ell T_o^2}{3Z\mu} .t = 4.2t \tag{14}$$

Thus for $t \gg 1$ second, use Equation 10 or its approximate form, Equation 12.

Consider a second example which might* be reasonable for a fire retardant (e.g., Phoschek):

$$T_o = 2.54 \times 10^{-2} \text{ (cm)} \tag{15}$$

$$\mu = 25 \text{ (poise)}$$

Other values in Equation 13.

*T_o is uncertain.

Then

$$\frac{2(a \cos \theta)\rho_{\ell} T_o^2}{3Z\mu} \cdot t = 1.7 \times 10^{-3} t \qquad (16)$$

Thus for $t >> 10^{-3}$ seconds, one may use either Equation 10 or Equation 12. Otherwise use Equation 10.

The examples indicate that after many minutes, films of water or water-like materials and films of fire retardant (e. g., Phoschek) with the physical characteristics given by Equations 13 and 15 would differ in thickness by the square root of the ratio of their viscosities. This assumes the value of T_o is such in each case that the approximation in Equation 12 is valid but the result is otherwise independent of T_o. Furthermore, it assumes that another process such as evaporation does not become dominant. The role of evaporation can be calculated for water and to less accuracy for fire retardant, given its physical characteristics.

APPENDIX D

CAPTURE PROGRAMS

INTRODUCTION

The programs described in this appendix implement the techniques described in the Honeywell report to the Northern Forest Fire Laboratory entitled "Capture of Retardants in Vertical Fuels," 21 August 1972. These programs were designed for the Honeywell Computer Network time sharing system using the Fortran IV language.

INPUT
(On Console)

PROGRAM: QUANT
Douglas fir, lodge pole

Line	Fortran Symbol	Description	Units	Format
1.	RAD	Radius of crown	feet	F10.5
	H	Height	feet	F10.5
	SE	Fuel particle effective mineral content	-	F10.5
	RLOAD	Total load of stand	pounds/feet^2	F10.5
2.	IO	Number of film thicknesses desired	-	I7
	FILMT	Film thicknesses	inches	5F10.5
3.	SA (J)	Surface area per level (4 levels)	feet^2/feet^2	4F10.5
4.	N	1	-	I7
	ALP	1. (constant)	-	F10.5
5.	NJ	Number of quantities to deliver	-	I7
	QI	Quantity delivered	gallons/feet^2	5F10.5
6.	RPERC (J)	Fraction of loading per level (4 levels)	-	4F10.5
7.	KL	Number of salt contents desired	-	I7
	SALT	Salt content	pounds/gallon	6F10.5

GLOSSARY

PROGRAM: QUANT

Fortran Symbol	Description	Units
WO (J)	Loading per level	pounds/feet^2
R (I)	Radius of rings	feet
R1CON	Adjusted radius RAD (1, 1)	feet
R2CON	Adjusted radius RAD (2, 2)	feet
R3CON	Adjusted radius RAD (3, 3)	feet
R4CON	Adjusted radius RAD (4, 4)	feet
AREA1	Area of AREA (1, 2), (1, 3)	feet^2
AREA2	Area of AREA (2, 3), (2, 4)	feet^2
AREA3	Area of AREA (3, 4)	feet^2
ARCO1	Adjusted area of AREA (1, 1)	feet^2
ARCO2	Adjusted area of AREA (2, 2)	feet^2
ARCO3	Adjusted area of AREA (2, 3)	feet^2
ARCO4	Adjusted area of AREA (2, 4)	feet^2
RNAR	Adjusted area of AREA (1, 4)	feet^2
VOL1	Volume of VOL (1, 2), (1, 3)	feet^3
VOL2	Volume of VOL (2, 3) (2, 4)	feet^3
VOL3	Volume of VOL (3, 4)	feet^3
AVOL1	Adjusted volume of VOL (1, 1)	feet^3
AVOL2	Adjusted volume of VOL (2, 2)	feet^3
AVOL3	Adjusted volume of VOL (3, 3)	feet^3
AVOL4	Adjusted volume of VOL (4, 4)	feet^3

GLOSSARY (Continued)

PROGRAM: QUANT

Fortran Symbol	Description	Units
VOLNAR	Adjusted volume of VOL (1, 4)	$feet^3$
RL1	Total area of level AREA (1)	$feet^2$
RL2	Total area of level 2 AREA (2)	$feet^2$
RL3	Total area of level 3 AREA (3)	$feet^2$
RL4	Total area of level 4 AREA (4)	$feet^2$
GF	Limit thickness	inches
C (I, J)	Amount captured per level and ring	gallons
G (I, J)	Coverage per level and ring	$gallons/feet^2$
Q (I, J)	Quantity dropping to next level	gallons
CU (I, J)	Fraction of level and ring coated	-
QG	Quantity reaching the ground	gallons
GG	Coverage of the ground	$gallons/feet^2$
RQ (I, J)	Amount of salt captured in each level and ring	pounds
REALC (I, J)	Concentration per level and ring	$pounds/feet^3$
ETA (I, J)	η_r per level and ring	-
BARQ (J)	Amount of salt captured on each level	pounds
ROWC (J)	Concentration for each level	$pounds/feet^3$
WETA (J)	Volume weighted η per level	-
ETARO (J)	Total η_r per level	-
CTREE	Concentration for total bush	$pounds/feet^3$
ETATVL	Volume weighted η_r for total bush	-

GLOSSARY (Concluded)

PROGRAM: QUANT

Fortran Symbol	Description	Units
ETATRE	Load weighted η_r for total bush	-
SUMQG	Total amount of retardant reaching the ground	gallons
GTOT	Total coverage of the ground	gallons/feet^2
QPERC	Fraction of retardant reaching the ground	-
TOTCOT	Total fraction of bush being coated	-
RANKET	"Ranking" weighted η_r	-

EQUATIONS

1. $GF = \Sigma(SA(J) * AREA(J)) / \Sigma AREA(J)$

2. $C(1,1),\ C(2,2),\ C(3,3),\ C(4,4) = ALP * SA(J) * AREA(I,J) * QI$

   $C(1,2),\ C(1,3),\ C(2,3),\ C(2,4),\ C(3,4) = ALP * SA(J) * Q(I, J-1)$

   $C(1,4) = ALP * SA(J) * AREA(I,J) * (I, J-1)/AREA(I,J)$

3. $G(I,J) = C(I,J)/AREA(I,J)$

4. $Q(I,J) = AREA(I,J) * Q(I, J-1) - C(I,J)$

5. $CO(I,J) = G(I,J)/GF$

6. $QG(I) = Q(I, J-1) - C(I,J)$

7. $GG(I) = QG(I)/AREA(I,J)$

8. $RQ(I,J) = ((SA(J) * 144 * FILMT * CO(I,J))/231) * SALT$

9. $REALC(I,J) = RQ(I,J)/WO(J)$

10. $ETA(I,J) = 1. - (1.6609 * (REALC(I,J) + SE)^{.23}$

11. $BARQ(J) = (\Sigma AREA(I,J) * RQ(I,J)/\Sigma AREA(I,J)$

12. $ROWC(J) = BARQ(J)/WO(J)$

13. $WETA(J) = \Sigma(VOL(I,J) * ETA(I,J))/VOL(I, J)$

14. $ETARO(J) = 1.\ (1.6609 * (ROWC(J) + SE))^{.23}$

15. $CTREE = \Sigma(BARQ(J) * AREA(J))/\Sigma(WO(J) * AREA(J))$

16. $ETATVL = \Sigma(ETARO(J) * AREA(J))/\Sigma AREA(J)$

17. $ETATRE = \Sigma(RPERC(J) * WETA(J))$

EQUATIONS (Concluded)

18. $SUMQG = \sum QG$

19. $GTOT = SUMQG / \pi * R(4)^2)$

20. $QPERC = SUMQG / \pi * RAD^2 * QI)$

21. $TOTCOT = \sum(CO(I, J) * AREA(I, J)) / \sum AREA(I, J)$

22. $RANKET = \{[4 * (AVOL4 * ETA(4, 4) + VOL3 * ETA(3, 4) + VOL2$
$*ETA(2, 4) + VOLNAR * ETA(1, 4) + AVOL2 * ETA(2, 2)$
$+AVOL3 * ETA(3, 3)] + [3* (VOL 1 * ETA(1, 3)$
$+VOL1 * ETA(2, 3))] + [(2 * VOL 1 * ETA(1, 2))$
$+(AVOL 1 * ETA(1, 1))]\} / \{[4 * AVOL4 +$
$VOL 3 + VOL 2 + VOLNAR + AVOL2 + AVOL3)] +$
$[(3. * (VOL1 + VOL2)) + (2 * VOL 1) + AVOL1]\}$

OUTPUT

			Units
1.	Initial conditions		
2.	Data per level and ring		
	a.	Radius of ring	feet
	b.	Amount of retardant captured	gallons
	c.	Amount of retardant droppong to next level	gallons
	d.	Coverage of section	gallons/feet^2
	e.	Fraction of area coated	
	f.	Concentration	pounds/feet^3
	g.	η_r	
	h.	Quantity of retardant reaching the ground	gallons
	i.	Coverage of the ground	gallons/feet^2
3.	Summary for each level		
	a.	Total concentration	pounds/feet^3
	b.	Total η_r	
4.	Summary for total bush		
	a.	Total amount of retardant to ground	gallons
	b.	Fraction of retardant not captured	
	c.	Coverage of ground	gallons/feet^2
	d.	Fraction of total bush coated	
	e.	Total concentration	pounds/feet^3
	f.	η_r based on load	
	g.	η_r based on volume	
	h.	"Ranking" weighted η_r	

PAGE 1

PROGRAM: QUANT

```
      DIMENSION C(9,9),Q(9,9),QG(9),ALP(9),R(9),G(9,9),GG(9),QI(9),
     + C0(10,10),CAP(8),SA(5),W0(5),SALT(8),ETA(8,8),REALC(8,8),
     + ETAR0(8),R0WC(8),RQ(9,9),BARQ(8),FILMT(8),RPERC(5),WETA(5)
      READ(9,1000) RAD,H,SE,RL0AD
      READ(9,1080) I0,(FILMT(I),I=1,I0)
      READ(9,1110) (SA(I),I=1,4)
      READ(9,1080) N,(ALP(J),J=1,N)
      READ(9,1080) NJ,(QI(J),J=1,NJ)
      READ(9,1110) (RPERC(J),J=1,4)
      READ(9,1080) KL,(SALT(J),J=1,KL)
      IH=KL
      KN=N
      D0 810 ID=1,I0
      D0 810 NK=1,NJ
      D0 810 KL=1,IH
      D0 810 N=1,KN
      CAP(1)=0.
      CAP(2)=0.
      CTREE=0.
      CAP(3)=0.
      SUMQG=0.
      D0 500 I=1,4
      W0(I)=RPERC(I)*RL0AD
  500 C0NTINUE
      R(1)=.25*RAD
      R1C0N=.57735*R(1)
      R(2)=.5*RAD
      R2C0N=SQRT((2.*R(2)**2-R(1)**2)/3.)
      R(3)=.75*RAD
      R3C0N=SQRT((3.*R(3)**2-2.*R(2)**2)/3.)
      R(4)=RAD
      R4C0N=SQRT((4.*R(4)**2-3.*R(3)**2)/3.)
      AREA1=(3.14159*R(1)**2)
      ARC01=3.14159*R1C0N**2
      AREA2=(3.14159*(R(2)**2-R(1)**2))
      ARC02=3.14159*(R2C0N**2-R(1)**2)
      AREA3=3.14159*(R(3)**2-R(2)**2)
      ARC03=3.14159*(R3C0N**2-R(2)**2)
      AREA4=3.14159*(R(4)**2-R(3)**2)
      ARC04=3.14159*(R4C0N**2-R(3)**2)
      RNAR=AREA1-(3.14159*(.2*RAD)**2)
      V0L1=AREA1*.25*H
      AV0L1=ARC01*.25*H
      V0L2=AREA2*.25*H
      AV0L2=ARC02*.25*H
      V0L3=AREA3*.25*H
      AV0L3=ARC03*.25*H
      V0L4=AREA4*.25*H
      AV0L4=ARC04*.25*H
      V0LNAR=RNAR*.25*H
      RL1=ARC01
      RL2=ARC02+AREA1
      RL3=ARC03+AREA2+AREA1
      RL4=ARC04+AREA3+AREA2+RNAR
      B0T=RL1+RL2+RL3+RL4
      T0P=RL1*SA(1)+RL2*SA(2)+RL3*SA(3)+RL4*SA(4)
```

PROGRAM: QUANT

```
      SBAR=T0P/B0T
      GF=SBAR*FILMT(ID)*.62337
      C(1,1)=ALP(N)*SA(1)*ARC01*QI(NK)
      IF(C(1,1).LT.0.) C(1,1)=0.
      G(1,1)=C(1,1)/ARC01
      IF(G(1,1).LE.GF) G0 T0 700
      C(1,1)=ARC01*GF
      G(1,1)=GF
700   Q(1,1)=AREA1*QI(NK)-C(1,1)
      IF(Q(1,1).LT.0.) Q(1,1)=0.
      C0(1,1)=G(1,1)/(GF)
      C(1,2)=ALP(N)*SA(2)*Q(1,1)
      IF(C(1,2).LT.0.) C(1,2)=0.
      G(1,2)=C(1,2)/AREA1
      IF(G(1,2).LE.GF) G0 T0 701
      C(1,2)=GF*AREA1
      G(1,2)=GF
701   IF(C(1,2).GT.Q(1,1)) C(1,2)=Q(1,1)
      Q(1,2)=Q(1,1)-C(1,2)
      IF(Q(1,2).LT.0.) Q(1,2)=0.
      C0(1,2)=G(1,2)/GF
      C(1,3)=ALP(N)*SA(3)*Q(1,2)
      IF(C(1,3).LT.0.) C(1,3)=0.
      G(1,3)=C(1,3)/AREA1
      IF(G(1,3).LE.GF) G0 T0 702
      C(1,3)=GF*AREA1
      G(1,3)=GF
702   IF(C(1,3).GT.Q(1,2)) C(1,3)=Q(1,2)
      Q(1,3)=Q(1,2)-C(1,3)
      IF (Q(1,3).LT.0.) Q(1,3)=0.
      C0(1,3)=G(1,3)/GF
      C(1,4)=ALP(N)*SA(4)*RNAR*(Q(1,3)/AREA1)
      IF(C(1,4).LT.0.) C(1,4)=0.
      G(1,4)=C(1,4)/RNAR
      IF(G(1,4).LE.GF) G0 T0 703
      C(1,4)=GF*RNAR
      G(1,4)=GF
703   IF(C(1,4).GT.Q(1,3)) C(1,4)=Q(1,3)
      QG(1)=Q(1,3)-C(1,4)
      IF(QG(1).LT.0) QG(1)=0.
      GG(1)=QG(1)/AREA1
      C0(1,4)=G(1,4)/(GF)
      CAP(1)=C0(1,1)*ARC01+C0(1,2)*AREA1+C0(1,3)*AREA1+C0(1,4)*RNAR
      AIR1=ARC01+AREA1+AREA1+RNAR
      D0 600 J=1,4
      R0(1,J)=((SA(J)*144.*FILMT(ID)*C0(1,J))/231.)*SALT(KL)
      REALC(1,J)=R0(1,J)/W0(J)
      ETA(1,J)=1.-(1.6609*(REALC(1,J)+SE)**.23)
      IF(ETA(1,J).LT.0.) ETA(1,J)=0.
600   CONTINUE
      C(2,2)=ALP(N)*SA(2)*ARC02*QI(NK)
      IF(C(2,2).LT.0.)C(2,2)=0.
      G(2,2)=C(2,2)/ARC02
      IF(G(2,2).LE.GF) G0 T0 704
      C(2,2)=GF*ARC02
      G(2,2)=GF
```

PROGRAM: QUANT

```
  660  704 Q(2,2)=AREA2*QI(NK)-C(2,2)
  665      IF(Q(2,2).LT.0.) Q(2,2)=0.
  670      C0(2,2)=G(2,2)/(GF)
  675      C(2,3)=ALP(N)*SA(3)*Q(2,2)
  680      IF(C(2,3).LT.0.) C(2,3)=0.
  685      G(2,3)=C(2,3)/AREA2
  690      IF(G(2,3).LE.GF) G0 T0 705
  695      C(2,3)=GF*AREA2
  700      G(2,3)=GF
  705  705 IF(C(2,3).GT.Q(2,2)) C(2,3)=Q(2,2)
  710      Q(2,3)=Q(2,2)-C(2,3)
  715      IF(Q(2,3).LT.0.) Q(2,3)=0.
  720     C0(2,3)=G(2,3)/GF
  725      C(2,4)=ALP(N)*SA(4)*Q(2,3)
  730      IF(C(2,4).LT.0.) C(2,4)=0.
  735      G(2,4)=C(2,4)/AREA2
  740      IF(G(2,4).LE.GF) G0 T0 706
  745      C(2,4)=GF*AREA2
  750      G(2,4)=GF
  755  706 IF(C(2,4).GT.Q(2,3)) C(2,4)=Q(2,3)
  760      QG(2)=Q(2,3)-C(2,4)
  765      IF(QG(2).LT.0.) QG(2)=0.
  770      GG(2)=QG(2)/AREA2
  775      C0(2,4)=G(2,4)/GF
  780      CAP(2)=C0(2,2)*ARC02+C0(2,3)*AREA2+C0(2,4)*AREA2
  785      AIR2=ARC02+AREA2+AREA2
  790      D0 601 J=2,4
  795      RQ(2,J)=((SA(J)*144.*FILMT(ID)*C0(2,J))/231.)*SALT(KL)
  800      REALC(2,J)=RQ(2,J)/W0(J)
  805      ETA(2,J)=1.-(1.6609*(REALC(2,J)+SE)**.23)
  810      IF(ETA(2,J).LT.0.) ETA(2,J)=0.
  815  601 CONTINUE
  820      C(3,3)=ALP(N)*SA(3)*ARC03*QI(NK)
  825      IF(C(3,3).LT.0.) C(3,3)=0.
  830      G(3,3)=C(3,3)/ARC03
  835      IF(G(3,3).LE.GF) G0 T0 707
  840      C(3,3)=ARC03*GF
  845      G(3,3)=GF
  850  707 Q(3,3)=AREA3*QI(NK)-C(3,3)
  855      IF(Q(3,3).LT.0.) Q(3,3)=0.
  860      C0(3,3)=G(3,3)/(GF)
  865      C(3,4)=ALP(N)*SA(4)*Q(3,3)
  870      IF(C(3,4).LT.0.) C(3,4)=0.
  875      G(3,4)=C(3,4)/AREA3
  880      IF(G(3,4).LE.GF) G0 T0 708
  885      C(3,4)=GF*AREA3
  890      G(3,4)=GF
  895  708 IF(C(3,4).GT.Q(3,3)) C(3,4)=Q(3,3)
  900      QG(3)=Q(3,3)-C(3,4)
  905      IF(QG(3).LT.0.) QG(3)=0.
  910      C0(3,4)=G(3,4)/GF
  915      GG(3)=QG(3)/AREA3
  920      CAP(3)=C0(3,3)*ARC03+C0(3,4)*AREA3
  925      AIR3=ARC03+AREA3
  930      D0 602 J=3,4
  935      RQ(3,J)=((SA(J)*144.*FILMT(ID)*C0(3,J))/231.)*SALT(KL)
```

PROGRAM: QUANT

```
      REALC(3,J)=RQ(3,J)/WQ(J)
      ETA(3,J)=1.-(1.6609*(REALC(3,J)+SE)**.23)
      IF(ETA(3,J).LT.0.) ETA(3,J)=0.
602   CONTINUE
      C(4,4)=ALP(N)*SA(4)*ARC04*QI(NK)
      IF(C(4,4).LT.0.) C(4,4)=0.
      G(4,4)=C(4,4)/ARC04
      IF(G(4,4).LE.GF) GO TO 709
      C(4,4)=ARC04*GF
      G(4,4)=GF
709   QG(4)=AREA4*QI(NK)-C(4,4)
      IF(QG(4).LT.0.) QG(4)=0.
      GG(4)=QG(4)/AREA4
      C0(4,4)=G(4,4)/(GF)
      CAP(4)=C0(4,4)*ARC04
      RQ(4,4)=((SA(4)*144.*FILMT(ID)*C0(4,4))/231.)*SALT(KL)
      REALC(4,4)=RQ(4,4)/WQ(4)
      ETA(4,4)=1.-(1.6609*(REALC(4,4)+SE)**.23)
      IF(ETA(4,4).LT.0.) ETA(4,4)=0.
      RQWC(1)=RQ(1,1)/WQ(1)
      BARQ(2)=(AREA1*RQ(1,2)+ARC02*RQ(2,2))/(AREA1+ARC02)
      RQWC(2)=BARQ(2)/WQ(2)
      AA=(AREA1*RQ(1,3)+AREA2*RQ(2,3)+ARC03*RQ(3,3))
      BARQ(3)=AA/(AREA1+AREA2+ARC03)
      BB=(RNAR*RQ(1,4)+AREA2*RQ(2,4)+AREA3*RQ(3,4)+ARC04*RQ(4,4))
      BARQ(4)=BB/(RNAR+AREA2+AREA3+ARC04)
      RQWC(3)=BARQ(3)/WQ(3)
      RQWC(4)=BARQ(4)/WQ(4)
      WETA(1)=ETA(1,1)
      WETA(2)=(VQL1*ETA(1,2)+AVQL2*ETA(2,2))/(VQL1+AVQL2)
      WET=VQL1*ETA(1,3)+VQL2*ETA(2,3)+AVQL3*ETA(3,3)
      WETA(3)=WET/(VQL1+VQL2+AVQL3)
      WE4=VQL1*ETA(1,4)+VQL2*ETA(2,4)+VQL3*ETA(3,4)+AVQL4*ETA(4,4)
      WETA(4)=WE4/(VQL1+VQL2+VQL3+AVQL4)
      DO 599 J=1,4
      ETARQ(J)=1.-(1.6609*(RQWC(J)+SE)**.23)
      IF(ETARQ(J).LT.0.) ETARQ(J)=0.
599   CONTINUE
      A1=ARC01
      A2=AREA1+ARC02
      A3=AREA1+AREA2+ARC03
      A4=RNAR+AREA2+AREA3+ARC04
      ARWQ=(WQ(1)*A1)+(WQ(2)*A2)+(WQ(3)*A3)+(WQ(4)*A4)
      CTREE=((RQ(1,1)*A1)+(A2*BARQ(2))+AA+BB)/ARWQ
      ETAR=(ETARQ(1)*A1)+(ETARQ(2)*A2)+(ETARQ(3)*A3)+(ETARQ(4)*A4)
      ETATVL=ETAR/(A1+A2+A3+A4)
      IF(ETATVL.LT.0.) ETATVL=0.
      TREAT1=RPERC(1)*WETA(1)+RPERC(2)*WETA(2)+RPERC(3)*WETA(3)
      ETATRE=TREAT1+RPERC(4)*WETA(4)
      IF(ETATRE.LT.0.) ETATRE=0.
      DO 805 K=1,4
      SUMQG=SUMQG+QG(K)
805   CONTINUE
      GTOT=SUMQG/(3.14159*R(4)**2)
      QPERC=SUMQG/(3.14159*RAD**2*QI(NK))
      SUBTQ=CAP(1)+CAP(2)+CAP(3)+CAP(4)
```

PROGRAM: QUANT

```
      T0TARE=AIR1+AIR2+AIR3+ARC04
      T0C0AT=(SUBT0)/T0TARE
      AB=AV0L4*ETA(4,4)+V0L3*ETA(3,4)+V0L2*ETA(2,4)+V0LNAR*ETA(1,4)
      ECD=4.*(AB+AV0L2*ETA(2,2)+AV0L3*ETA(3,3))
      DE=3.*(V0L1*ETA(1,3)+V0L2*ETA(2,3))
      DE2=(2.*V0L1*ETA(1,2))+(AV0L1*ETA(1,1))
      B0T1=4.*(AV0L4+V0L3+V0L2+V0LNAR+AV0L2+AV0L3)
      B0T2=(3.*(V0L1+V0L2))+(2.*V0L1)+AV0L1
      RANKET=(ECD+DE+DE2)/(B0T1+B0T2)
      WRITE(9,1090) ALP(N),QI(NK),SALT(KL),FILMT(ID)
      D0 806 I=1,4
      WRITE(9,1070) I
      WRITE(9,1095) R(I)
      IF(I.EQ.1) WRITE(9,1010) (C(I,J),J=1,4),(Q(I,J),J=1,3),
     +  (G(I,J),J=1,4),(C0(I,J),J=1,4),(REALC(I,J),J=1,4),
     + (ETA(I,J),J=1,4)
      IF(I.EQ.2) WRITE(9,1020) (C(I,J),J=2,4),(Q(I,J),J=2,3),
     +  (G(I,J),J=2,4),(C0(I,J),J=2,4),(REALC(I,J),J=2,4),
     +  (ETA(I,J),J=2,4)
      IF(I.EQ.3) WRITE(9,1030) (C(I,J),J=3,4),Q(3,3),
     +  (G(I,J),J=3,4),(C0(I,J),J=3,4),(REALC(I,J),J=3,4),
     +  (ETA(I,J),J=3,4)
      IF(I.EQ.4) WRITE(9,1040) C(4,4),G(4,4),C0(4,4),REALC(4,4),ETA
      WRITE(9,1050) QG(I),GG(I)
  806 CONTINUE
      WRITE(9,1100) (R0WC(J),J=1,4),(ETAR0(J),J=1,4),(WETA(J),J=1,4
      WRITE(9,1060) SUMQG,QPERC,GT0T,T0C0AT,CTREE,ETATRE,ETATVL,RAN
  810 CONTINUE
 1000 FORMAT (8F10.5)
 1010 FORMAT ('AM0UNT CAPTURED IN   ',4F12.5,/,
     +        'AM0UNT T0 NEXT LEVEL ',3F12.5,/,
     +        'GALL0NS/SQ.FT.       ',4F12.5,/,
     +         'PERCENT C0ATED       ',4F12.5,/,
     +         'C VALUE              ',4F12.5,/,
     +         'ETA-SUB-R            ',4F12.5,/)
 1020 FORMAT ('AM0UNT CAPTURED IN   ',12X,3F12.5,/,
     +        'AM0UNT T0 NEXT LEVEL ',12X,2F12.5,/,
     +        'GALL0NS/SQ.FT.       ',12X,3F12.5,/,
     +         'PERCENT C0ATED       ',12X,3F12.5,/,
     +  'C VALUE              ',12X,3F12.5,/,
     +  'ETA-SUB-R            ',12X,3F12.5,/)
 1030 FORMAT ('AM0UNT CAPTURED IN   ',24X,2F12.5,/,
     +        'AM0UNT T0 NEXT LEVEL ',24X,F12.5,/,
     +        'GALL0NS/SQ.FT.       ',24X,2F12.5,/,
     +         'PERCENT C0ATED       ',24X,2F12.5,/,
     +  'C VALUE              ',24X,2F12.5,/,
     +  'ETA-SUB-R            ',24X,2F12.5,/)
 1040 FORMAT ('AM0UNT CAPTURED IN   ',36X,F12.5,/,
     +        'GALL0NS/SQ.FT.       ',36X,F12.5,/,
     +         'PERCENT C0ATED       ',36X,F12.5,/,
     +  'C VALUE              ',36X,F12.5,/,
     +  'ETA-SUB-R            ',36X,F12.5,/)
 1050 FORMAT ('0UANTITY T0 GR0UND = ',F10.5,/,
     +  'GALL0NS/SQ.FT.      = ',F10.5,/)
 1060 FORMAT ('T0TAL AM0UNT T0 GR0UND        = ',F10.5,/,
     +  'FRACTI0N N0T CAPTURED         = ',F10.5,/,
```

PROGRAM: QUANT

```
 1500    +  'GALLONS/SQ.FT.                    = ',F10.5,/,
 1505    +  'PERCENT COATED                    = ',F10.5,/,
 1510    +  'TOTAL C VALUE                     = ',F10.5,/,
 1515    +  'ETA-SUB-R  (TOTAL TREE) (LOAD)= ',F10.5,/,
 1520    +  'ETA-SUB-R  (TOTAL TREE) (VOL) = ',F10.5,/,
 1525    +  '"RANKING" WEIGHTED ETA-SUB-R  = ',F10.5,//////)
 1530 1070 FORMAT ('RING  ',I2,'      LEVEL = ',6X,'1',11X,'2',
 1535    +  11X,'3',11X,'4')
 1540 1080 FORMAT (I7,6F10.5)
 1545 1090 FORMAT ('ALPHA = ',F8.4,/,'GAL/FT= ',F8.4,/,'SALT/GAL=',F8.5,
 1550    +  'FILM TH.=',F8.5,//)
 1555 1095 FORMAT ('RADIUS = ',F8.5)
 1560 1100 FORMAT ('TOT. C FOR THE ROW  ',4F12.5,/,
 1565    +         'TOT ETA FOR THE ROW ',4F12.5,/,
 1570    +         'WEIGHTED ETA FOR ROW',4F12.5,//)
 1575 1110 FORMAT (5F10.5)
 1580      STOP
 1585      END
```

```
ALPHA =   1.0000
GAL/FT=   0.0200
SALT/GAL= 2.00000
FILM TH.= 0.01200
```

RING 1 LEVEL =	1	2	3	4
RADIUS = 3.32500				
AMOUNT CAPTURED IN	0.01934	0.05803	0.05803	0.02089
AMOUNT TO NEXT LEVEL	0.67530	0.61727	0.55925	
GALLONS/SQ.FT.	0.00167	0.00167	0.00167	0.00167
PERCENT COATED	1.00000	1.00000	1.00000	1.00000
C VALUE	0.05857	0.04158	0.03338	0.03301
ETA-SUB-R	0.10328	0.16013	0.19292	0.19451

QUANTITY TO GROUND = 0.53836
GALLONS/SQ.FT. = 0.01550

RING 2 LEVEL =	1	2	3	4
RADIUS = 6.65000				
AMOUNT CAPTURED IN		0.07737	0.17408	0.17408
AMOUNT TO NEXT LEVEL		2.00656	1.83248	
GALLONS/SQ.FT.		0.00167	0.00167	0.00167
PERCENT COATED		1.00000	1.00000	1.00000
C VALUE		0.04158	0.03338	0.03301
ETA-SUB-R		0.16013	0.19292	0.19451

QUANTITY TO GROUND = 1.65840
GALLONS/SQ.FT. = 0.01592

RING 3 LEVEL =	1	2	3	4
RADIUS = 9.97500				
AMØUNT CAPTURED IN			0.13540	0.29014
AMØUNT TØ NEXT LEVEL			3.33783	
GALLØNS/SQ.FT.			0.00167	0.00167
PERCENT CØATED			1.00000	1.00000
C VALUE			0.03338	0.03301
ETA-SUB-R			0.19292	0.19451

QUANTITY TØ GRØUND =	3.04769
GALLØNS/SQ.FT. =	0.01755

RING 4 LEVEL =	1	2	3	4
RADIUS = 13.30000				
AMØUNT CAPTURED IN				0.19343
GALLØNS/SQ.FT.				0.00167
PERCENT CØATED				1.00000
C VALUE				0.03301
ETA-SUB-R				0.19451

QUANTITY TØ GRØUND =	4.66909
GALLØNS/SQ.FT. =	0.01920

TØT. C FØR THE RØW	0.05857	0.04158	0.03338	0.03301
TØT ETA FØR THE RØW	0.10328	0.16013	0.19292	0.19451
WEIGHTED ETA FØR RØW	0.10328	0.16013	0.19292	0.19451

TØTAL AMØUNT TØ GRØUND =	9.91353
FRACTIØN NØT CAPTURED =	0.89196
GALLØNS/SQ.FT. =	0.01784
PERCENT CØATED =	1.00000
TØTAL C VALUE =	0.03410
ETA-SUB-R (TØTAL TREE) (LØAD)=	0.17877
ETA-SUB-R (TØTAL TREE) (VØL) =	0.18868
"RANKING" WEIGHTED ETA-SUB-R =	0.19033

INPUT
(On Console)

PROGRAM: QUACH2
Chaparral Bush

Line	Fortran Symbol	Description	Units	Format
1.	RAD	Radius of crown	feet	F10. 5
	H	Height	feet	F10. 5
	SE	Fuel particle effective mineral content	-	F10. 5
	RELOAD	Total load of stand	pounds/feet^2	F10. 5
2.	IO	Number of film thicknesses desired	-	I7
	FILMT	Film thicknesses	inches	5F10. 5
3.	SAC (J)	Surface area per level (4 levels)	feet^2/feet^2	4F10. 5
4.	N	1	-	I7
	ALP	1. constant	-	F10. 5
5.	NJ	Number of quantities to deliver	-	I7
	QI	Quantity delivered	gallons/feet^2	5F10. 5
6.	RPERC (J)	Fraction of loading per level (4 levels)	-	4F10. 5
7.	KL	Number of salt contents desired	-	17
	SALT	Salt content	pounds/gallon	6F10. 5

GLOSSARY

Fortran Symbol	Description	Units
WO (J)	Loading per level	pounds/feet^2
R	Radius of ring	feet
R1CON	Adjusted radius R (1, 1) & R (1, 4)	feet
R2CON	Adjusted radius R (2, 2), R (2, 3)	feet
AREA1	Area of AREA (1, 2) & (1, 3)	feet^2
ARCO1	Area of AREA (1, 1) & (1, 4)	feet^2
ARCO4	Area of AREA (2, 2) & (2, 3)	feet^2
VOL 1	Volume of VOL (1, 2) & (1, 3)	feet^3
AVOL 1	Volume of VOL (1, 1) & (1, 4)	feet^3
AVOL 2	Volume of VOL (2, 2) & (2, 3)	feet^3
RL1	Total area of level 1 and 4 AREA (1) & (4)	feet^2
RL 2	Total area of level 2 and 3 AREA (2) & (3)	feet^2
GF	Limit thickness	inches
C (I, J)	Amount captured per level and ring	gallons
G (I, J)	Coverage per level and ring	gallons/feet^2
Q (I, J)	Quantity dropping to next level	gallons
CO (I, J)	Fraction of level and ring coated	-
QG	Quantity reaching the ground	gallons
GG	Coverage of the ground	gallons/feet^2
RQ (I, J)	Amount of salt captured in each level and ring	pounds
REALC (I, J)	Concentration per level and ring	pounds/feet^3

GLOSSARY (Concluded)

Fortran Symbol	Description	Units
ETA (I, J)	η_r per level and ring	-
BARQ (J)	Amount of salt captured in each level	pounds
ROWC (J)	Concentration for each level	pounds/feet^3
WETA (J)	Volume weighted η_r per level	-
ETARO (J)	Total η_r per level	-
CTREE	Concentration for total bush	pounds/feet^3
ETATVL	Volume weighted η_r for total bush	-
ETATREE	Load weighted η_r for total bush	-
SUMQG	Total amount of retardant reaching the ground	gallons
GTOT	Total coverage of the ground	gallons/feet^2
QPERC	Fraction of retardant reaching the ground	-
TOTCOT	Total fraction of bush being coated	-
RANKET	"Ranking" weighted η_r	-

Equations Used in QUACH2 For Chaparral Bush

1. $GF = (RL1 * SA(1) + RL2 * SA(2) + RL2 * SA(3) + RL1 * SA(4)) / (2 * RL1 + 2 * RL2) * FILMT * .62337$

2. $C(1,1)$ & $C(2,2) = ALP * SA(J) * AREA(I,J) * QI$
   $C(1,2)$ & $C(1,3) = ALP * SA(J) * Q(I, J-1)$
   $C(1,4)$ & $C(2,3) = ALP * SA(J) * AREA(I,J) * Q(I, J-1)\ AREA(I,J)$

3. $G(I,J) = C(I,J)/AREA(I,J)$

4. $Q(I,J) = AREA(I,J) * Q(I,J-1) - C(I,J)$

5. $CO(I,J) = G(I,J)/GF$

6. $QG(I) = Q(I,J-1) - C(I,J)$

7. $GG(I) = QG(I)/AREA(I,J)$

8. $RQ(I,J) = ((SA(J) * 144 * FILMT * CO(I,J))/231) * SALT$

9. $REALC(I,J) = RQ(I,J)/WO(J)$

10. $ETA(I,J) = 1. - (1.6609 * (REALC(I,J) + SE)^{.23}$

11. $BARQ(J) = (\sum AREA(I,J) * RQ(I,J)) / \sum AREA(I,J))$

12. $ROWC(J) = BARQ(J)/WO(J)$

13. $WETA(J) = \sum(VOL(I,J) * ETA(I,J))/\sum VOL(I,J)$

14. $ETARO(J) = 1. - (1.6609 * (ROWC(J) + SE)^{.23}$

15. $CTREE = \sum(BARQ(J) * AREA(J))/\sum(WO(J) * AREA(J))$

16. $ETATVL = \sum(ETARO(J) * AREA(J)) / \sum AREA(J)$

17. $ETATRE = \sum(RPERC(J) * WETA(J))$

18. $SUMQG = \sum QG$

19. $GTOT = SUMQG/(3.1459 * R(2)^2$

20. $QPERC = SUMQG/(3.14159 * RAD^2 * QI)$

21. $TOTCOT = (3/(4 * \pi * RAD^2)) * \sum(CO(I,J) * AREA(I,J))$

Equations Used in QUACH2 For Chaparral Bush (Concluded)

22. RANKET = [(AVOL1 * ETA (1, 1) + AVOL2 * ETA (2, 2) + AVOL2 * ETA (2, 3)
+ AVOL1 * ETA (1, 4)) * 3 + 2 * VOL 1 * ETA (1, 2)
+ VOL 1 * ETA (1, 3))]/ (3* VOL (I, J))

OUTPUT

			Units
1.	Initial conditions		
2.	Data per level and ring		
	a.	Radius of ring	feet
	b.	Amount of retardant captured	gallons
	c.	Amount of retardant dropping to next level	gallons
	d.	Coverage of section	gallons/feet^2
	e.	Fraction of area coated	
	f.	Concentration	pounds/feet^3
	g.	η_r	
	h.	Quantity of retardant reaching the ground	gallons
	i.	Coverage of the ground	gallons/feet^2
3.	Summary for each level		
	a.	Total concentration	pounds/feet^3
	b.	Total η_r	
4.	Summary for total bush		
	a.	Total amount of retardant to ground	gallons
	b.	Fraction of retardant not captured	
	c.	Coverage of ground	gallons/feet^2
	d.	Fraction of total bush coated	
	e.	Total concentration	pounds/feet^3
	f.	η_r based on load	
	g.	η_r based on volume	
	h.	"Ranking" weighted η_r	

PAGE 1

PROGRAM: QUACH2

```
      DIMENSION C(9,9),Q(9,9),QG(9),ALP(9),R(9),G(9,9),GG(9),QI(9),
     + C0(10,10),SA(5),SALT(8),ETA(8,8),REALC(8,8),ETAR0(8),R0WC(8),
     + W0(8),RQ(8,8),BARQ(8),FILMT(8),RPERC(5),WETA(5)
      READ(9,1000) RAD,H,SE,RL0AD
      READ(9,1080) I0,(FILMT(I),I=1,I0)
      READ(9,1110) (SA(I),I=1,4)
      READ(9,1080) N,(ALP(I),I=1,N)
      READ(9,1080) NJ,(QI(I),I=1,NJ)
      READ(9,1110) (RPERC(J),J=1,4)
      READ(9,1080) KL,(SALT(J),J=1,KL)
      KN=N
      D0 810 ID=1,I0
      D0 810 NK=1,NJ
      D0 810 N=1,KN
      D0 810 IG=1,KL
      CAP1=0.
      SUMQG=0.
      D0 599 I=1,4
      W0(I)=RPERC(I)*RL0AD
599   C0NTINUE
      R(1)=.5*RAD
      R1C0N=.57735*R(1)
      R(2)=RAD
      R2C0N=SQRT((2.*R(2)**2-R(1)**2)/3.)
      AREA1=(3.14159*R(1)**2)
      ARC01=3.14159*R1C0N**2
      AREA4=3.14159*(R(2)**2-R(1)**2)
      ARC04=3.14159*(R2C0N**2-R(1)**2)
      V0L1=AREA1*.25*H
      AV0L1=ARC01*.25*H
      AV0L2=ARC04*.25*H
      RL1=ARC01
      RL2=ARC04*AREA1
      B0T=2.*RL1+2.*RL2
      T0P=RL1*SA(1)+RL2*SA(2)+RL2*SA(3)+RL1*SA(4)
      SBAR=T0P/B0T
      GF=SBAR*FILMT(ID)*.62337
      C(1,1)=ALP(N)*SA(1)*ARC01*QI(NK)
      IF(C(1,1).LT.0.) C(1,1)=0.
      G(1,1)=C(1,1)/ARC01
      IF(G(1,1).LE.GF) G0 T0 700
      C(1,1)=GF*ARC01
      G(1,1)=GF
700   Q(1,1)=AREA1*QI(NK)-C(1,1)
      IF(Q(1,1).LT.0.) Q(1,1)=0.
      C0(1,1)=G(1,1)/GF
      C(1,2)=ALP(N)*SA(2)*Q(1,1)
      IF(C(1,2).LT.0.) C(1,2)=0.
      G(1,2)=C(1,2)/AREA1
      IF(G(1,2).LE.GF) G0 T0 701
      C(1,2)=GF*AREA1
      G(1,2)=GF
701   IF(C(1,2).GT.Q(1,1)) C(1,2)=Q(1,1)
      Q(1,2)=Q(1,1)-C(1,2)
      IF(Q(1,2).LT.0.) Q(1,2)=0.
      C0(1,2)=G(1,2)/GF
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PRØGRAM: QUACH2

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      C(1,3)=ALP(N)*SA(3)*Q(1,2)
      IF(C(1,3).LT.0.) C(1,3)=0.
      G(1,3)=C(1,3)/AREA1
      IF(G(1,3).LE.GF) GØ TØ 702
      C(1,3)=GF*AREA1
      G(1,3)=GF
  702 IF(C(1,3).GT.Q(1,2)) C(1,3)=Q(1,2)
      Q(1,3)=Q(1,2)-C(1,3)
      IF (Q(1,3).LT.0.) Q(1,3)=0.
      CØ(1,3)=G(1,3)/GF
      C(1,4)=ALP(N)*SA(4)*ARCØ1*(Q(1,3)/AREA1)
      IF(C(1,4).LT.0.) C(1,4)=0.
      G(1,4)=C(1,4)/ARCØ1
      IF(G(1,4).LE.GF) GØ TØ 703
      C(1,4)=ARCØ1*GF
      G(1,4)=GF
  703 IF(C(1,4).GT.Q(1,3)) C(1,4)=Q(1,3)
      QG(1)=Q(1,3)-C(1,4)
      IF(QG(1).LT.0) QG(1)=0.
      GG(1)=QG(1)/AREA1
      CØ(1,4)=G(1,4)/GF
      DØ 600 J=1,4
      RQ(1,J)=((SA(J)*144.*FILMT(ID)*CØ(1,J))/231.)*SALT(IG)
      REALC(1,J)=RQ(1,J)/WØ(J)
      ETA(1,J)=1.-(1.6609*(REALC(1,J)+SE)**.23)
      IF(ETA(1,J).LT.0.) ETA(1,J)=0.
  600 CØNTINUE
      C(2,2)=ALP(N)*SA(2)*ARCØ4*QI(NK)
      IF(C(2,2).LT.0.)C(2,2)=0.
      G(2,2)=C(2,2)/ARCØ4
      IF(G(2,2).LE.GF) GØ TØ 704
      C(2,2)=ARCØ4*GF
      G(2,2)=GF
  704 Q(2,2)=3.14159*(R(2)**2-R(1)**2)*QI(NK)-C(2,2)
      IF(Q(2,2).LT.0.) Q(2,2)=0.
      CØ(2,2)=G(2,2)/GF
      C(2,3)=ALP(N)*SA(3)*ARCØ4*(Q(2,2)/AREA4)
      IF(C(2,3).LT.0.) C(2,3)=0.
      G(2,3)=C(2,3)/ARCØ4
      IF(G(2,3).LE.GF) GØ TØ 705
      C(2,3)=ARCØ4*GF
      G(2,3)=GF
  705 IF(C(2,3).GT.Q(2,2)) C(2,3)=Q(2,2)
      Q(2,3)=Q(2,2)-C(2,3)
      IF(Q(2,3).LT.0.) Q(2,3)=0.
      QG(2)=Q(2,2)-C(2,3)
      IF(QG(2).LT.0.) QG(2)=0.
      GG(2)=QG(2)/AREA4
      CØ(2,3)=G(2,3)/GF
      DØ 601 J=2,3
      RQ(2,J)=((SA(J)*144.*FILMT(ID)*CØ(2,J))/231.)*SALT(IG)
      REALC(2,J)=RQ(2,J)/WØ(J)
      ETA(2,J)=1.-(1.6609*(REALC(2,J)+SE)**.23)
      IF(ETA(2,J).LT.0.) ETA(2,J)=0.
  601 CØNTINUE
      BARQ(1)=RQ(1,1)
```

PROGRAM: QUACH2

```
      R0WC(1)=RQ(1,1)/W0(1)
      BARQ(2)=(AREA1*RQ(1,2)+ARC04*RQ(2,2))/(AREA1+ARC04)
      R0WC(2)=BARQ(2)/W0(2)
      BARQ(3)=(AREA1*RQ(1,3)+ARC04*RQ(2,3))/(AREA1+ARC04)
      BARQ(4)=RQ(1,4)
      R0WC(3)=BARQ(3)/W0(3)
      R0WC(4)=RQ(1,4)/W0(4)
     WETA(1)=ETA(1,1)
     WETA(2)=(V0L1*ETA(1,2)+AV0L2*ETA(2,3))/(V0L1+AV0L2)
     WETA(3)=(V0L1*ETA(1,3)+AV0L2*ETA(2,3))/(V0L1+AV0L2)
     WETA(4)=ETA(1,4)
      D0 609 J=1,4
      ETAR0(J)=1.-(1.6609*(R0WC(J)+SE)**.23)
      IF(ETAR0(J).LT.0.) ETAR0(J)=0.
  609 CONTINUE
      A1=ARC01
      A2=AREA1+ARC04
      ARW0=(W0(1)*A1)+(W0(2)*A2)+(W0(3)*A2)+(W0(4)*A1)
      CTREE=((BARQ(1)*A1)+(BARQ(2)*A2)+(BARQ(3)*A2)+(BARQ(4)*A1))/A
      ETAR=ETAR0(1)*A1+ETAR0(2)*A2+ETAR0(3)*A2+ETAR0(4)*A1
      ETATVL=ETAR/(A1+A2+A2+A1)
      IF(ETATVL.LT.0.) ETATVL=0.
     ATR=RPERC(1)*WETA(1)+RPERC(2)*WETA(2)+RPERC(3)*WETA(3)
     ETATRE=ATR+RPERC(4)*WETA(4)
      IF(ETATRE.LT.0.) ETATRE=0.
      D0 805 K=1,2
      SUMQG=SUMQG+QG(K)
  805 CONTINUE
      GT0T=SUMQG/(3.14159*R(2)**2)
      QPERC=SUMQG/(3.14159*RAD**2*QI(NK))
      SUBT0=C0(1,1)*ARC01+C0(1,2)*AREA1+C0(1,3)*AREA1+C0(1,4)*ARC01
       SUBT2=C0(2,2)*ARC04+C0(2,3)*ARC04+SUBT0
      T0TC0T=(3./(4.*3.14159*RAD**2))*SUBT2
      AB1=AV0L1*ETA(1,1)+AV0L2*ETA(2,2)+AV0L2*ETA(2,3)
      AB2=3.*(AB1+AV0L1*ETA(1,4))
      DE=2.*(V0L1*ETA(1,2)+V0L1*ETA(1,3))
      RL0WER=(3.*(2.*AV0L2+2.*AV0L1))+(2.*(2.*V0L1))
      RANKET=(AB2+DE)/RL0WER
      WRITE(9,1090) ALP(N),QI(NK),SALT(IG),FILMT(ID)
      D0 806 I=1,2
      WRITE(9,1070) I
      WRITE(9,1095) R(I)
      IF(I.EQ.1) WRITE(9,1010) (C(I,J),J=1,4),(Q(I,J),J=1,3),
     +  (G(I,J),J=1,4),(C0(I,J),J=1,4),(REALC(I,J),J=1,4),
     +  (ETA(I,J),J=1,4)
      IF(I.EQ.2) WRITE(9,1020) (C(I,J),J=2,3),(Q(I,J),J=2,2),
     +  (G(I,J),J=2,3),(C0(I,J),J=2,3),(REALC(I,J),J=2,3),
     +  (ETA(I,J),J=2,3)
      WRITE(9,1050) QG(I),GG(I)
  806 CONTINUE
      WRITE(9,1100) (R0WC(J),J=1,4),(ETAR0(J),J=1,4)
      WRITE(9,1060) SUMQG,QPERC,GT0T,T0TC0T,CTREE,ETATRE,ETATVL,RAN
  810 CONTINUE
 1000 FORMAT (8F10.5)
 1010 FORMAT ('AMOUNT CAPTURED IN    ',4F12.5,/,
     +        'AMOUNT TO NEXT LEVEL ',3F12.5,/,
```

PROGRAM: QUACH2

```
  895    +            'GALLONS/SQ.FT.        ',4F12.5,/,
  900    +             'PERCENT COATED        ',4F12.5,/,
  905    +             'C VALUE               ',4F12.5,/,
  910    +             'ETA-SUB-R             ',4F12.5,/)
  915 1020 FORMAT ('AMOUNT CAPTURED IN   ',12X,2F12.5,/,
  920    +           'AMOUNT TO NEXT LEVEL ',12X,F12.5,/,
  925    +           'GALLONS/SQ.FT.       ',12X,2F12.5,/,
  930    +            'PERCENT COATED       ',12X,2F12.5,/,
  935    +            'C VALUE              ',12X,2F12.5,/,
  940    +            'ETA-SUB-R            ',12X,2F12.5,/)
  945 1050 FORMAT ('QUANTITY TO GROUND = ',F10.5,/,
  950    + 'GALLONS/SQ.FT.     = ',F10.5,/)
  955 1060 FORMAT ('TOTAL AMOUNT TO GROUND        = ',F10.5,/,
  960    + 'FRACTION NOT CAPTURED          = ',F10.5,/,
  965    + 'GALLONS/SQ.FT.                 = ',F10.5,/,
  970    + 'PERCENT COATED                 = ',F10.5,/,
  975    + 'TOTAL C VALUE                  = ',F10.5,/,
  980    + 'ETA-SUB-R  (TOTAL BUSH) (LOAD)= ',F10.5,/,
  985    + 'ETA-SUB-R  (TOTAL BUSH) (VOL) = ',F10.5,/,
  990    + '"RANKING" WEIGHTED ETA-SUB-R  = ',F10.5,/////)
  995 1070 FORMAT (' RING ',I2,'      LEVEL = ',6X,'1',11X,'2',
 1000    + 11X,'3',11X,'4',/)
 1005 1080 FORMAT (I7,6F10.5)
 1010 1090 FORMAT ('ALPHA = ',F9.5,/,'GAL/FT= ',F9.5,/,
 1015    + 'SALT/GAL=',F9.5,/,'FILM TH.=',F9.5,//)
 1020 1095 FORMAT ('RADIUS = ',F8.5)
 1025 1100 FORMAT ('TOT. C FOR THE ROW   ',4F12.5,/,
 1030    +          'TOT ETA FOR THE ROW  ',4F12.5,//)
 1035 1110 FORMAT (5F10.5)
 1040      STOP
 1045      END
```

```
FØRTRAN QUACH2,S


ALPHA =    1.00000
GAL/FT=    0.04000
SALT/GAL=  2.00000
FILM TH.=  0.02000

 RING  1       LEVEL =        1          2          3          4

RADIUS =  1.66650
AMØUNT CAPTURED IN          0.05234    0.15702    0.13963    0.00000
AMØUNT TØ NEXT LEVEL        0.29666    0.13963    0.00000
GALLØNS/SQ.FT.              0.01800    0.01800    0.01661    0.00000
PERCENT CØATED              1.00000    1.00000    0.92307    0.00000
C VALUE                     0.22678    0.22665    0.20917    0.00000
ETA-SUB-R                   0.00000    0.00000    0.00000    0.42410

QUANTITY TØ GRØUND =     0.00000
GALLØNS/SQ.FT.     =     0.00000

 RING  2       LEVEL =        1          2          3          4

RADIUS =  3.33300
AMØUNT CAPTURED IN                     0.20936    0.20936
AMØUNT TØ NEXT LEVEL                   0.83763
GALLØNS/SQ.FT.                         0.01800    0.01800
PERCENT CØATED                         1.00000    1.00000
C VALUE                                0.22665    0.22661
ETA-SUB-R                              0.00000    0.00000

QUANTITY TØ GRØUND =     0.62827
GALLØNS/SQ.FT.     =     0.02400

TØT. C FØR THE RØW          0.22678    0.22665    0.21914    0.00000
TØT ETA FØR THE RØW         0.00000    0.00000    0.00000    0.42410


TØTAL AMØUNT TØ GRØUND          =    0.62827
FRACTIØN NØT CAPTURED           =    0.45005
GALLØNS/SQ.FT.                  =    0.01800
PERCENT CØATED                  =    0.92308
TØTAL C VALUE                   =    0.21050
ETA-SUB-R  (TØTAL BUSH) (LØAD)=      0.10815
ETA-SUB-R  (TØTAL BUSH) (VØL) =      0.02651
"RANKING" WEIGHTED ETA-SUB-R    =    0.03029
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